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Multislice Mining for Thick Western Coal Seams

By T. D. Hackett, D. L. Boreck,
and D. R. Clarke

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(United States. Bureau of Mines)

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	min	minute
ft	foot	pct	percent
ft/min	foot per minute	psi	pound per square inch
lb/ft^3	pound per cubic foot	st	short ton
m	meter	yr	year

MULTISLICE MINING FOR THICK WESTERN COAL SEAMS

By T. D. Hackett,[1] D. L. Boreck,[2] and D. R. Clarke[3]

ABSTRACT

Multislice mining methods were analyzed by the U.S. Bureau of Mines to determine their application to western United States thick coal seams; ground control, geology, and costs were considered. Multislice mining is used in widely varying seam conditions worldwide, including flat seams too thick to mine in a single pass, pitching thick seams, and seams containing a rock parting. Longwall multislice methods predominate, but room-and-pillar variants also exist. The initial use of the method in western seams is planned at a deep Colorado mine where a rock parting will be used to separate two slices mined by longwall.

Ground control and spontaneous combustion are major hazards associated with multislice mining. A well-consolidated upper slice gob can reduce ground control problems and provide a seal against spontaneous combustion. Geologic analysis indicates that the consolidation of the gob depends on the composition of the upper slice roof, the presence of water, and sufficient overburden pressure. A geologically competent intermediate rock parting can also reduce ground control problems and seal against spontaneous combustion.

To compete in western coal markets, the cost of multislice mining must be within the range of normal longwall costs. Analysis indicates that multislice operating costs should be within this range, and that multislice mining costs decrease as panel width increases. Relatively wide (600 to 800 ft) panels also provide increased coal recovery.

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INTRODUCTION

The western region of the United States contains extensive coal reserves. The Energy Information Administration of the U.S. Department of Energy (*1*)[4] estimates that the western region's demonstrated reserve base contains 236.7 billion st, of which 141.0 billion st, or 59.6 pct, must be mined by underground methods. Recently, a single deposit containing 113 billion st, i.e., up to 182 ft thick and under 1,100 ft of overburden, was located by the U.S. Geological Survey (*2*) in the Powder River Basin of Wyoming. A significant percentage of these reserves lie in thick seams that are too deep for surface mining and have a thickness that exceeds the height limits of existing underground mining equipment, requiring a portion of the seam to be left in the mine. The frequent occurrence of thick seams in Colorado, Utah, and Wyoming has been reported by Boreck (*3*). For this report, a thick seam is defined as a seam 15 ft thick or greater. The definition also includes minable seams that are split from a thick seam, or closely spaced minable coal seams where one of the two seams will be lost should standard mining methods be used. Because the highest longwall face being used in the United States as of 1987 is 14 to 15 ft high, that portion of the seam thickness in excess of 15 ft cannot be mined. In addition, thick seams frequently contain partings (and are termed split seams) that cannot be economically taken with the coal, requiring the portion of the seam above or below the parting to be left. It will be shown later in the report that coal recovery in seams with partings and in closely spaced multiple seams with interburden of less than 30 ft can be greatly improved with multislice mining. In order to improve recovery in thick seams, the U.S. Bureau of Mines has investigated the multislice mining method.

Multislice mining (also called multilift or multileaf mining) is the extraction of a thick coal seam in successive levels, usually proceeding downward in the seam so that later levels or slices underlay previous ones. Figure 1 schematically shows a cross section with three slices worked downward in succession and some technical features commonly used in the method. The uppermost two slices work a continuous thick seam, allowing the roof to cave behind the faces. To provide a safe roof in the middle slice, an artificial roof is emplaced on the floor of the first slice. The artificial roof, composed of wire mesh or other material, keeps the first slice gob from caving into the second slice working areas. In the lowermost third slice, a seam parting provides an advantageous roof layer, and an artificial roof is not necessary. Numerous variations in the multislice method are possible. For instance, adjacent slices may be mined simultaneously, or mining of underlying slices may be delayed to permit gob consolidation in the upper slice. Stowing may be used to prevent roof caving. Also, room-and-pillar methods exist.

Nonsimultaneous multislice mining without artificial roof was previously identified by Oitto (*4*) as best adapted to western mining conditions. The geologic factors affecting the development of thick and closely spaced seams have been discussed by Boreck (*3*). These factors include the thickness and configuration of the seam and the roof composition and variability. Hackett (*5*) analyzed the ground control of multislice mining. The stress on the upper slice gob and the consolidation of the gob were determined to be important for lower slice mining. Multislice layouts have been designed for an existing western mine (*6*) and, under contract to the Bureau,[5] for a hypothetical 100-ft-thick western seam. Measures to prevent and control spontaneous combustion have also been discussed (*7*). The layout, geological factors, ground control, and cost of multislice mining are discussed in this report.

TYPES OF MULTISLICE MINING

Numerous variations of multislice mining have been used worldwide to get high coal recovery under local conditions of geology, subsidence control, proneness to spontaneous combustion, statutes, and economics. Australia, United Kingdom, China, France, Germany, Hungary, India, Japan, Poland, Romania, Spain, Yugoslavia, and the U.S.S.R. have practiced or now practice multislice mining. Approximately 41 pct of China's coal production comes from multislice mining (*8*), and they have mined as many as 10 overlying slices (*9*). Because local conditions vary widely, the multislice geometry and techniques used vary markedly. The conditions under which the method has been used have often been difficult and restrictive, showing the technical feasibility of the method.

Figure 2 shows one method of classifying multislice mining methods. Other classifications have been used, and not every possible multislice variation is shown. The branches shown lead to multislice methods that conform to U. S. mining practice. In the course of the discussion of the various multislice methods, those that have inherently high cost, low productivity, or other problems, such as difficult ground control, will be identified. The discussion will be structured on figure 2, emphasizing those practices that conform to U.S. mining practice.

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[4]Italic numbers in parentheses refer to items in the list of references at the end of this report.

[5]Contract H0262035, "Design and Evaluation of a Coal Mine Entry System For Longwall Top Slicing of Thick Coal Seams" to D'Appolonia Consulting Engineers, Inc.

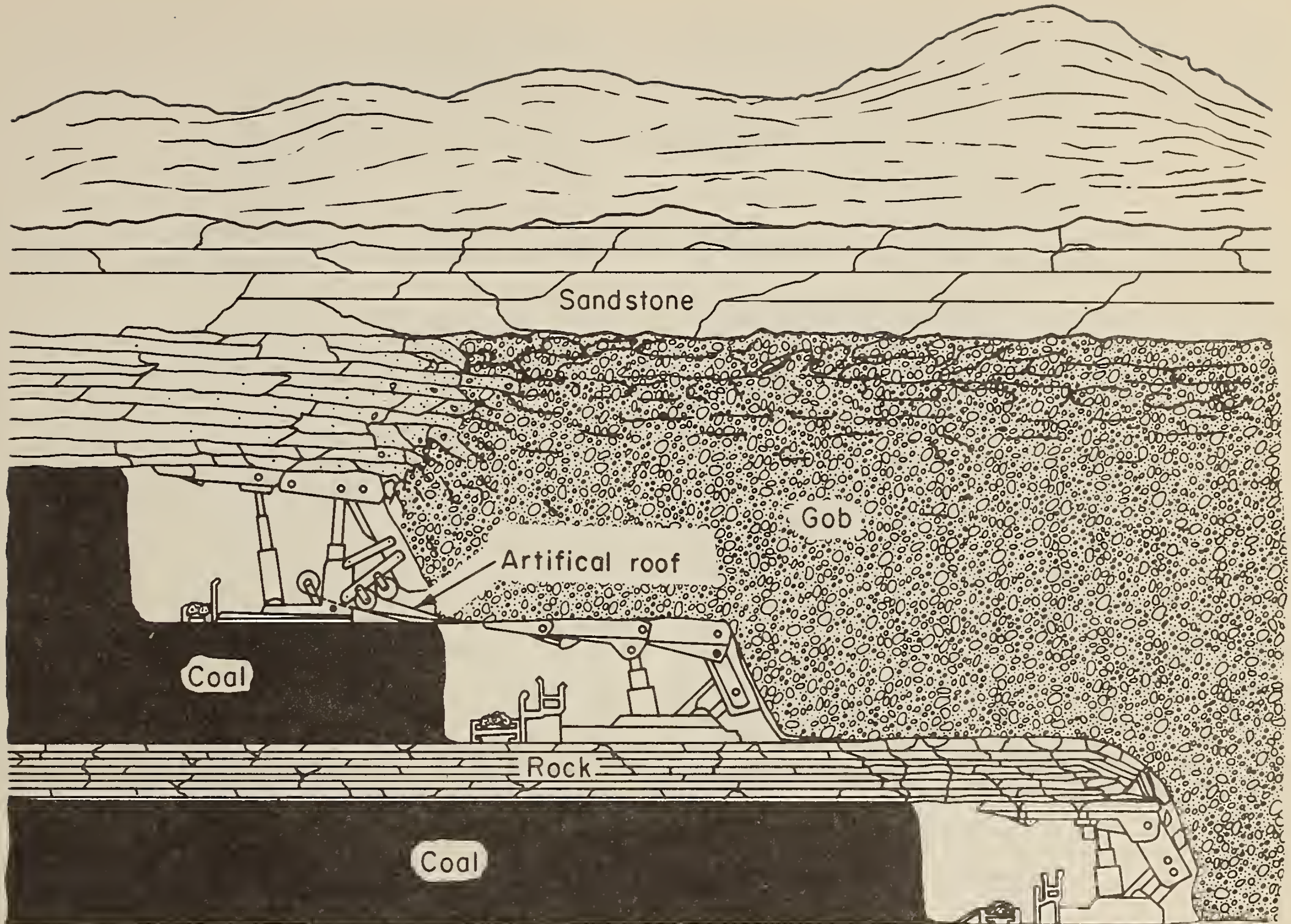


Figure 1.–Schematic cross section of multislice mining.

ASCENDING MULTISLICE

Multislice mining can proceed either downward (descending multislice, often called top slicing) or upwards (ascending multislice) from the bottom of the seam or other horizon. Ascending methods normally backfill behind the working face to provide a base for the next slice. Backfill is used where surface structures must be protected from subsidence (*10-13*), the overlying coal must be sealed to prevent spontaneous combustion (*10-12, 14*), when the seam has a massive roof that will not cave (*15-17*), or in undersea mining (*11, 18*).

Ascending multislice is frequently used in thick, steeply dipping seams. The horizontal slicing method (fig. 3*A*) divides the coal seam into slices running along the seam strike and across the seam horizontally. Stowing or hydraulic backfill is placed during extraction to support the unmined coal above and provide a working floor for overlying slices. In ascending inclined slicing (fig. 3*B*) a slice at the bottom of the seam is extracted, and successive overlying slices worked on the backfill material. A variation on horizontal slicing, termed the ascending-descending method, was proposed for steep, thick seams in India (*19*). The seam is divided into blocks down the dip. Each block is worked with ascending slicing, and the blocks are worked in descending sequence. Horizontal and inclined slicing can also be done in descending order. Ascending methods have the disadvantages that the backfill does not completely support the overlying coal and the coal may fracture, causing spontaneous combustion problems in overlying slices. Three to four slices are reported to be the limit for ascending multislice (*20*).

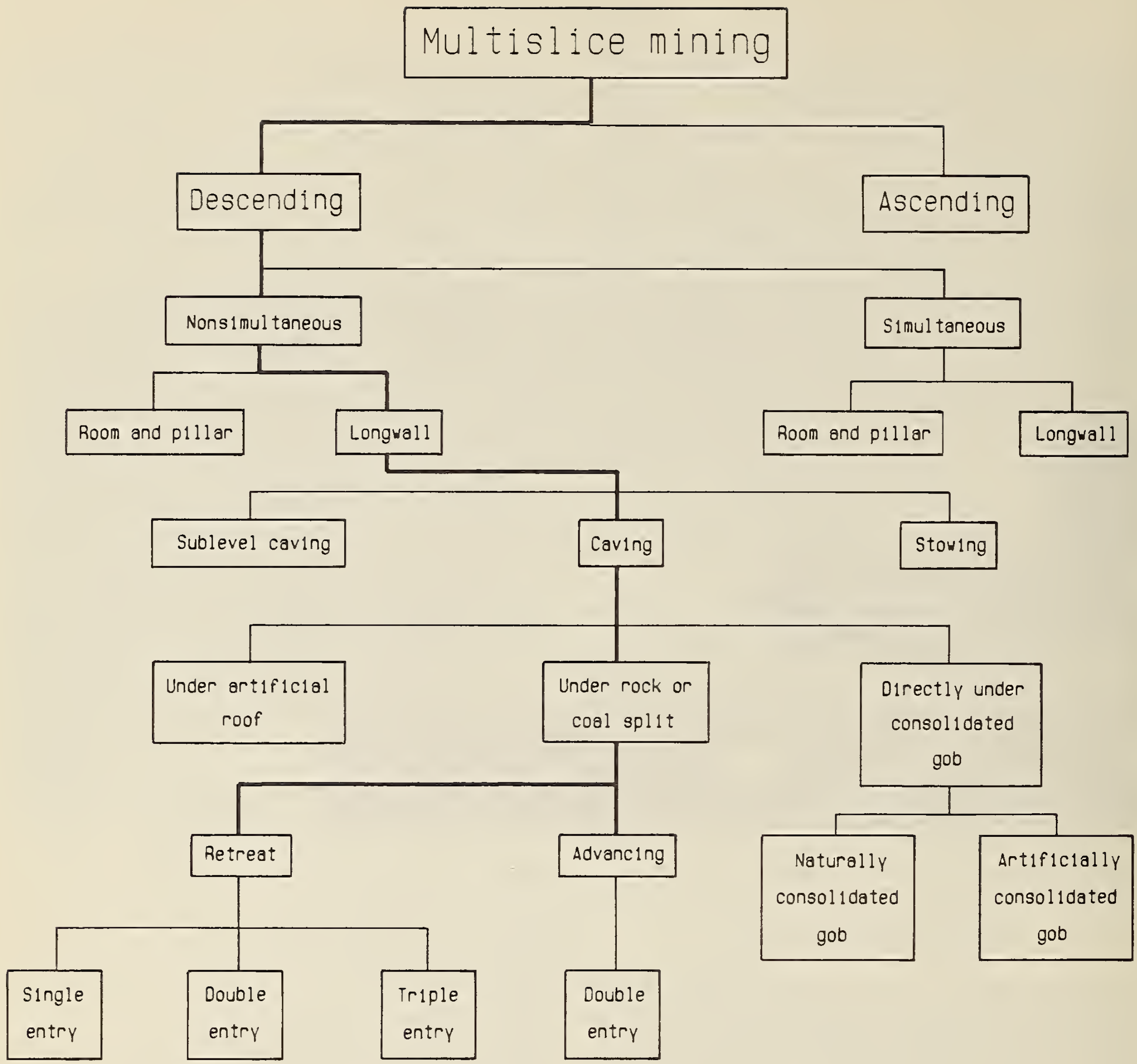


Figure 2.–Classification of multislice mining methods.

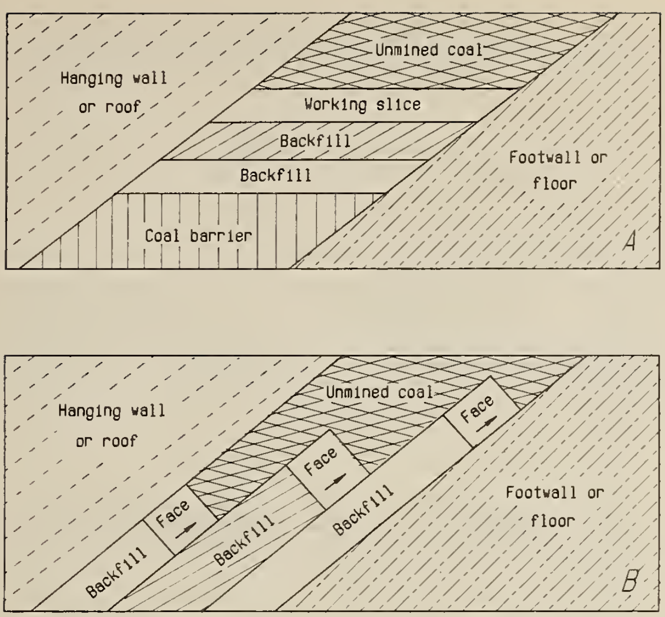


Figure 3.–Cross section of ascending multislice mining methods. ***A*, Horizontal slicing; *B*, inclined slicing.**

DESCENDING MULTISLICE

Descending multislice methods are more commonly used than ascending methods because they are adaptable to a wider range of mining and geologic conditions (*20*). Either simultaneous or nonsimultaneous mining can be used. In simultaneous multislice, two or more faces follow each other directly in the coal seam at the same time. It is desirable to keep a constant distance or lag between the faces to avoid ground control problems (*4*). Nonsimultaneous methods disassociate operations in the slices by completely extracting the overlying slice before lower slice mining starts. A variable period of time is left between the slices to keep lower slices out of the influence of upper slices and permit the upper slice gob to settle. Descending methods have a number of advantages. First, the roof is allowed to cave, eliminating the need for stowing. Secondly, the roof supports and mining equipment work on a solid coal floor rather than having to work on weak backfill.

In descending multislice, some means is required to provide a safe roof for the lower slice. Separating the slices is especially important in simultaneous multislice as the overlying gob has not had time to consolidate. This function can be accomplished several different ways. In figure 4*A*, artificial roof material placed during upper slice mining is used to separate the slices. The lag necessary in simultaneous mining is indicated. An intermediate rock or coal band can separate the slices as in figure 4*B*. This method eliminates the cost of artificial roof, but if a coal band is used, coal recovery is reduced, and the coal left in the gob may create spontaneous combustion problems. Upper slices have also been backfilled (fig. 4*C*). In India (*15*), simultaneous mining with pneumatically stowed backfill cemented with fly ash in the upper slice was used to extract a 5-m-thick seam with hard-to-cave roof. The methods shown in figure 4 can apply to both simultaneous and nonsimultaneous multislice mining.

Simultaneous Multislice

Simultaneous multislice has the disadvantage of face interdependence (*21*). If one face stops for maintenance or ground control problems, the other face must also stop, totally eliminating production. Nonsimultaneous mining disassociates operations in the slices by completely extracting overlying slices before lower slice mining starts. Faces are independent in that one face does not stop other faces.

In the Karaganda Basin of the U.S.S.R., a 7.0- to 7.5-m-thick seam was mined by simultaneous mechanized longwalls in two slices, with a lag between the faces of 40 to 60 m (*22*). A band of coal 0.5 to 0.8 m thick was left between slices to provide a roof for the lower slice face.

An artificial roof placed while mining the top lift is frequently used to separate lower slices from overlying gob material. The roof may be laid on the upper slice support canopies (*23*) or on the floor (*24*). In the Miike Colliery in Japan (*25*), overlapping panels or wire mesh were laid on the floor in front of a support with a shortened base, which allows room to work. The lower face lagged the upper by about 40 m. Oitto (*4*) further discusses simultaneous multislice mining in Japan. In Chinese mines, roof of plastic mesh is being experimented with. Because of the large number of slices mined, roadways are driven in the seam floor (*26*).

Nonsimultaneous Multislice

Nonsimultaneous multislice can be divided into longwall methods and room-and-pillar methods. Longwall methods are most common, but an interesting room-and-pillar method has been tested in Australia (*27*). A trial of two-slice extraction was conducted in a 5.4-m-thick seam. The top slice was mined using a continuous miner and a pillar extraction method termed the Wongawilli split-and-fender system. In this mining system, panels are developed by parallel double entries on the panel edges. Fenders between the double entries are extracted by retreating toward the mains. A coal parting or septum 1.8 m thick constituted the middle slice. The lower slice was extracted with a split-and-fender system, and the septum was taken down by raising the boom of the continuous miner. Grouted wooden dowels supported the septum and were used as a guide to indicate the correct roof level on the lower slice. They were inserted in the floor during top slice mining. The trial achieved 62 pct full seam recovery and showed it was possible to extract Australian thick seams using continuous miners. Lower slice mining started after upper slice mining was completed, but it may be possible to mine upper and lower slices simultaneously.

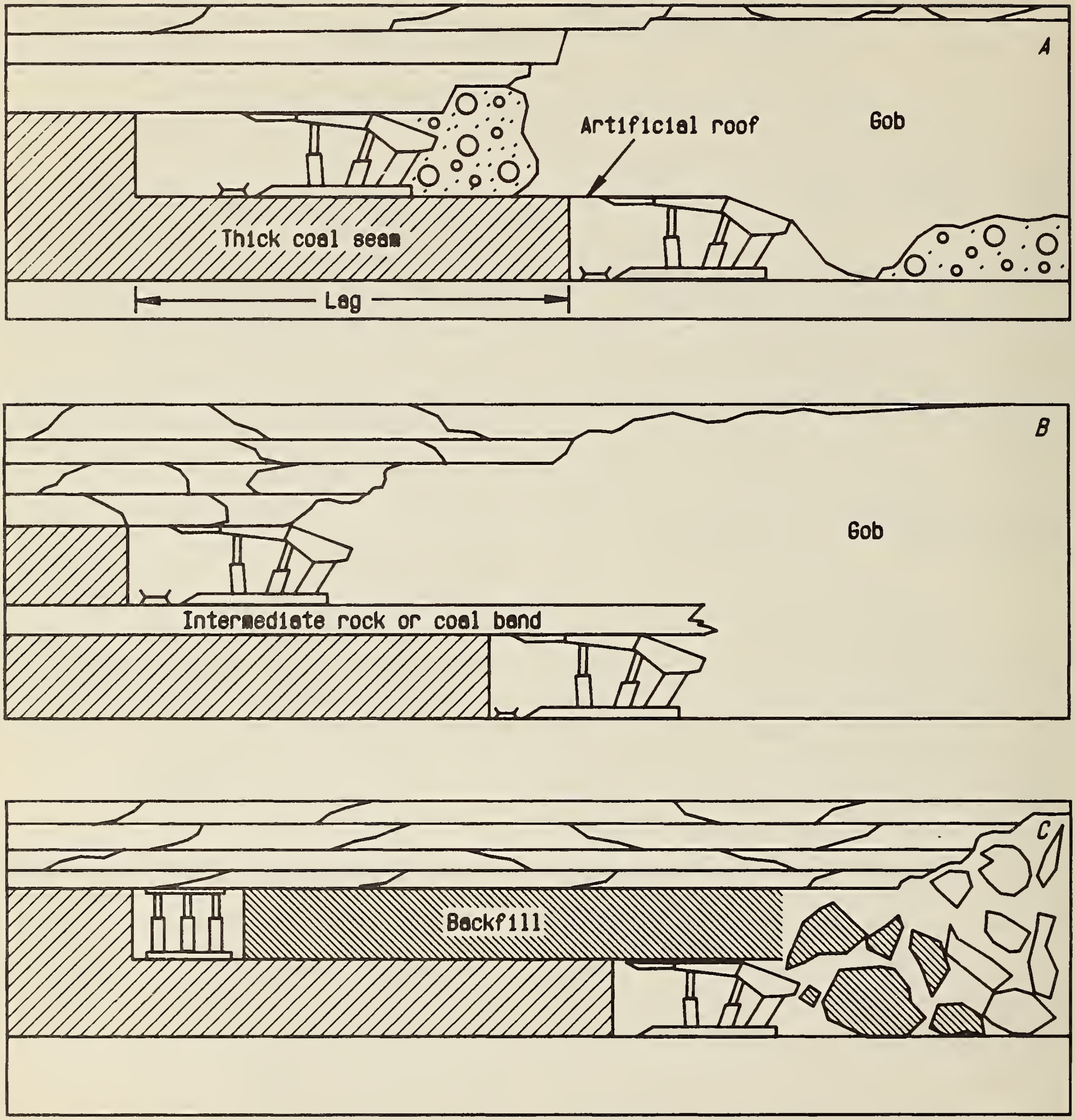


Figure 4.–Cross section of descending simultaneous multislice mining methods. *A*, With artificial roof separating slices; *B*, with intermediate rock parting; *C*, with backfill in upper slice.

Nonsimultaneous longwall methods include sublevel caving, stowing methods, and methods with roof caving. Sublevel caving is practiced in France (*28*), Hungary (*29*), and Yugoslavia (*30-31*). It can be used to extract up to a 10-m-thick slice in one or two passes. Coal is mined by a combination of standard longwall and roof caving (fig. 5). Three meters of coal at the bottom of the slice are mined by standard longwall and approximately 7 m of coal in the roof are extracted by caving through gates in the gob shield or canopies of specialized face supports. The caved coal loads onto a conveyor in the rear of the supports, or directly onto the face conveyor. In France (*28*), the caved roof coal was held back by wire mesh behind the supports. The mesh was cut, allowing the coal to flow into a second conveyor between the support legs. Specialized face supports, called banana props, were used to agitate the coal by raising and lowering the legs to improve drawing. Seventy percent of sublevel caving coal production typically comes from the caving operation and 30 pct from the longwall (*32*). Blasting may be necessary to destress the caved part of the slice. At least three overlying 10-m-thick slices can be worked.

Descending simultaneous multislice longwall with backfilling in the upper slice and caving in the lower slice has been used as previously noted (*15*). In Czechoslovakia (*13*), the upper slice waste is usually backfilled when mining a thick seam in descending lifts.

Multislice Mining with Roof Caving

While stowing has some advantages in protecting surface structures from subsidence (*33*), it is expensive and labor intensive (*14*). Longwall methods that allow the roof to cave have now become the preferred technology, and where stowing is not required to protect surface structures or to achieve some other objective, would be a preferred method for U.S. multislice mining. Also, higher capacity shield supports have now replaced chock-type supports,

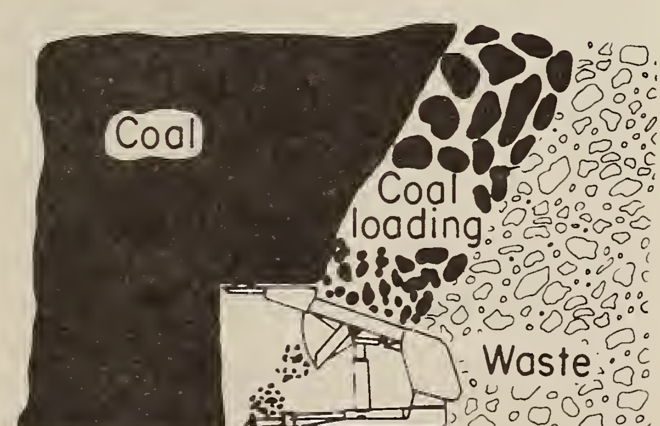


Figure 5.–Cross section of longwall caving method.

allowing the caving of massive roof that formerly required other methods of mining. Using caving methods, there exists the danger that upper slice gob could cave into the lower slice workings. To prevent this occurrence, some means is needed to either separate the slices (for example with artificial roof or an intermediate rock band) or stabilize the gob.

In simultaneous descending multislice (previously discussed), an artificial roof is used to separate the slices. Artificial roof might also be used in nonsimultaneous descending multislice, but corrosive mine water and/or heat from spontaneous combustion in the upper slice gob might deteriorate the roof material. One alternative method used to provide stable roof is to exploit the natural tendency of the gob to reconsolidate. Given sufficient time and pressure and the right material and amount of water, the gob can consolidate to form a lower slice roof. Polish mines have used gob as a lower slice roof (*34*). A period of 3 to 5 yr passed between working upper and lower slices, and successful results were obtained only when roof rocks were within a certain range of mechanical properties. Reconsolidated roof is possible when the roof consists of argillaceous rocks, and appropriate water is present (*11*). Under optimum conditions, sufficient consolidation can occur after 3 months. In China, if the roof is argillaceous shale, and it consolidates in the presence of water, a reconsolidated roof for the next slice can form in 6 to 12 months (*9, 23*).

Another alternative to artificial roof is to artificially consolidate the gob by injecting water combined with fly ash or other additives. The water promotes consolidation of the gob material, and the additive settles to the bottom of the gob to form a solid roof layer. A seal against spontaneous combustion is also created. Chemical consolidation of the gob has been used in Hungary to provide a compacted lower slice roof (*14*). Cement grout, with a composition depending on the chemical composition and fragmentation of the gob, was injected through perforated pipe laid in floor trenches. The artificial roof produced was 30 to 50 cm thick and sealed the upper slice gob, providing a safeguard against spontaneous combustion. Loess mud has been injected into the gob in China, allowing extraction of more than 10 slices without occurrence of spontaneous combustion (*26*). Mud injection can improve the reconsolidation of the gob and reduce the time necessary to reconsolidate (*9*). Artificial gob consolidation has also been used in Czechoslovakia (*13*) and in Japan with washery waste (*21*).

Use of either artificial roof or artificial gob consolidation entails extra expense. Emplacement of the roof material or grout material requires extra labor and transportation underground, and the cost of roof material or grout must be borne. The cost for artificial roof can amount to 20 pct of the total coal cost per metric ton (*11*). One method to eliminate this cost and effort is to leave a band of rock or coal to separate the slices and form a lower slice roof. Where seams contain a rock split, the split has been advantageously used as lower slice roof. It

is preferable to leave rock rather than coal if the coal is prone to spontaneous combustion. In Japan, a 1.5- to 2.0-m thick rock band separated simultaneous multislice faces at the Kushiro Colliery in Hokkaido (*21*). Forty-five units (upper plus lower slice), making up 90 faces, were mined with this method. The use of a coal band or septum to separate room-and-pillar slices in the Australian Wongawilli system was previously discussed. In the U.S.S.R., a 0.5- to 0.8-m band of coal separated simultaneous multislice faces (*22*). A 3-m-thick rock split will form the lower slice roof in a planned trial of nonsimultaneous multislice mining at the Dutch Creek Mine near Redstone, CO.

MULTISLICE MINING METHODS AND LAYOUTS FOR THICK WESTERN COAL SEAMS

If multislice mining is to be used in the United States, it must conform to American economic, safety, and legal requirements. Cost is a primary consideration because if costs are not competitive, the method will not be used. Many of the multislice methods used in other countries would not be cost competitive because of extra labor and material requirements or poor productive capacity. Improvements in technology, such as mechanized placement of artificial roof, may reduce the labor requirements and costs for some methods. The following discussion is directed primarily to flat-lying, thick seams. However, steep thick seams exist in the Grand Hogback area of Colorado (*35*), and multislice operations adapted to steep thick seams may have application.

Descending, nonsimultaneous, longwall, which allows roof caving and uses an intermediate rock band as the lower slice roof (fig. 4*B*), may be the multislice method best suited to U. S. mining requirements. Ascending multislice requires expensive stowing material and placement systems, which descending multislice does not require. Nonsimultaneous longwall has the advantage of separating the slices in time, allowing the upper slice gob to consolidate and reducing the interference of mining operations in one slice on the other slice. Longwall with roof caving has become the preferred method worldwide and is standard practice in the United States. Artificial roof can provide good lower slice conditions, but is expensive and slows retreat of the face. Recent developments in mechanization of roof laying may reduce the cost of artificial roof, but if the artificial roof can be eliminated altogether, costs will be even lower. A rock band offers a relatively cheap method to separate the slices. The method has been successfully used abroad, and applicable conditions exist in the United States.

In figure 2, the heavy black line leads to multislice variants that may have application in thick, relatively flat western coal seams. Retreat and advancing longwall methods are indicated. Retreat is the most commonly used longwall method in the United States. Advancing longwall is currently being used in one mine in Colorado (*36*) where the top 3 m of a 6-m seam is being mined, leaving a 3-m-thick intermediate rock band. Multislice mining underneath the rock parting is planned (*37*).

A major difference between United States and foreign longwall practice is the type of entry system used to develop the longwall panel. Head-tail entries in countries other than the United States are typically single entries. In the United States, a minimum of two entries must be used, and three- and four-entry systems are the most common. American longwall development entries also differ in cross section and support. A rectangular entry section with a flat roof and roof bolts are used, rather than a semicircular cross section with arches. In the United Kingdom, rectangular entries are sometimes used, especially in retreat mining.

If standard U.S. longwall practice can be adapted to multislice mining, introduction of the method will be easier than nonstandard practice that does not conform to U.S. legal and safety requirements is used. Two- and three-entry systems are the standard longwall development systems in the western States where thick seams amenable to multislice mining exist. They provide acceptable cost, good ground control conditions, adequate ventilation cross section, adequate room for belts, and access for rubber-tired man trip vehicles and supply vehicles. They also conform to U.S. legal requirements. Single-entry systems avoid some ground control and spontaneous combustion problems and have been recommended for multislice mining of very thick coal seams. The remnant chain pillars left by multiple entries can cause stress concentrations in underlying slices and contribute to the occurrence of spontaneous combustion, especially if the pillars are crushed. However, single entries are not currently legal in the United States. Congestion and equipment interference, entailing a loss in productivity, can occur, and there may be insufficient room for rubber-tired man trip vehicles and supply vehicles.

A multislice mining operation has been designed for a hypothetical 100-ft-thick western coal seam. The complex design incorporates single-entry pillarless mining for longwall development and ten 10-ft-high slices. More than 100 yr would be required to extract the full seam thickness. To provide long-term stability required to keep the mine openings accessible for 100 yr, the mains were located in the seam floor. The method proposed is similar to Chinese multislice mining in thick seams, where main headings are driven in the floor of the coal seam, and a minimum of protective pillars are left for pillarless mining (*9*). An alternative to multislice mining of a 100-ft seam might be sublevel caving. Up to 10 m can be extracted in one combined longwall and caving slice (*30*), possibly reducing the required number of slices from 10 to only 3 or 4.

A nonsimultaneous multislice operation has been designed for an existing 500-ft-deep thick seam in Utah (*6*). Two-entry longwall development was selected for both the upper and lower slices. A 3.5-ft-thick coal or rock parting would be left to separate the 7-ft slices. A modified

two-entry system was planned for the lower slice. The lower slice chain pillars were designed wider than the upper slice chain pillars, permitting the lower slice development to be used for adjacent lower slices. Lower slice entries were located (inset) 85 ft inside the mined-out panel of the upper slice. Access entries between the mains and lower slice were designed to pass directly underneath the mains barrier pillar. Similarly, lower slice crosscuts would pass directly under upper slice chain pillars. The expected stress concentration underneath the upper slice chain pillar was considered low enough to provide adequate crosscut stability.

MULTISLICE GROUND CONTROL

Poor ground control constitutes both a safety hazard and a major cost. Roof falls continue to be a major cause of mining accidents, and the cost of cleaning up and resupporting roof falls is high in terms of labor and lost production. In a multislice operation, should a roof fall occur in the lower slice roof and propagate into the upper slice gob, it might create a severe hazard and possibly result in loss of the lower slice face.

For an experimental operation such as multislice mining, it is desirable to get the best possible ground control. One approach to achieving this objective would be to locate multislice workings, as much as possible, in areas where better ground control is expected. A multislice mining plan based on the expected locations of good and poor ground control would greatly improve the chances of success of the operation.

PLANNING MULTISLICE GROUND CONTROL

Multislice mining consists of three stages, each of which must be accomplished in sequence to successfully get the coal out of the mine. These three stages experience different strata stresses and conditions, and separate ground control plans are needed for each. The first stage is to access the lower slice. Access entries and roof support must contend with upper slice abutment stresses. The development of the head-tail entries, if retreat mining is to be used, is the second stage. The condition of the lower slice roof and time are major ground control factors to be dealt with. The third stage is longwall mining of the lower slice. The condition of the lower slice roof is again a major factor.

The following discussion pertains to the lower slice of a multislice operation. Because multislice mining has not been done in the United States, the discussion is necessarily hypothetical.

Access Entries

If more than one slice is to be mined, an extremely complex access entry system may be needed, as is the case for the 100-ft-thick seam extracted in 10 slices. As the number of slices increases, interaction between the slices and ground control problems also build up. If only two slices are to be extracted, the access entry system can be simpler, and ground control problems should be fewer.

To reach the lower slice, the entries must pass underneath the barrier pillar between the mains and the panel, or the chain pillars between upper slice panels. Both structures sustain the upper slice abutment stresses, which will also load the access entries where they pass underneath. The increased stress under the abutment and resultant fractures in the floor material may cause squeeze, floor heave, or roof instability. Ground control problems may be increased by the requirement that the access entries remain open and safe for the entire life of the lower slice panel. Because the lower slice entries are below existing grade, water may collect there and cause ground control problems and bog down equipment.

Lower Slice Development Entries

Lower slice head-tail entries will need to remain open and safe for the period of time required to develop and mine the lower slice panel, if retreat longwall is used. If advancing longwall is used, the entries must remain open for the period of time necessary to advance and recover the panel. Good roof stability needs to be maintained during that period. Planning factors to be considered include the stress on the entry system and the condition and strength of the lower slice roof.

If the lower slice entries are located in a destressed zone, as previously discussed, this is beneficial. However, a better understanding of gob stress and site-specific information will be needed to predict actual stresses on entry systems at future multislice sites.

In the western United States, the first multislice operations will probably work under a seam parting rather than under artificial roof or directly under consolidated gob. The thickness, geology, and condition of the parting will have an effect on the stability of the lower slice roof. These factors are discussed in a later section of this report.

Lower Slice Longwall Mining

The stability of the roof is a major consideration during this stage of mining. If a roof fall occurs between the face-support canopy and the face, there is the danger that it may propagate into the overlying gob material. Thus, consolidated gob is desirable to limit the extent of the fall. If a rock parting is used to separate the slices, the condition and stress of the parting are important. Naturally occurring fractures, such as joints (discussed later), may decrease parting strength. It is possible that fractures may be induced by upper slice mining. Because of the overlying gob, roof action may be different than in standard longwall. Hypothetically, the weaker gob and parting should not be able to sustain large spans of hanging roof

behind the face supports. Water may be present in the gob and cause wet conditions on the lower slice face.

LOCATION OF LOWER SLICE WORKINGS

Ground control conditions on the lower slice will be a major factor in determining the success or failure of the multislice operation. Thus, the lower slice needs to be located and laid out to provide a safe and productive ground control environment. Any feature that increases stresses on lower slice workings, or weakens lower slice roof, can result in poor ground control. Widespread mining experience has shown that high stresses and poor mining conditions are usually encountered under remnant pillars, whereas good conditions are encountered under gob (*5*). Unmined pillars in overlying seams can transfer load concentrations to underlying workings (*38*) and result in bumps (*39*). These observations, with associated ground control theory, can form a logical basis for locating lower slice workings and identifying areas of potentially poor ground control.

When a longwall panel is mined, a portion of the load originally carried by the panel coal is transferred to the abutments because of the poor load-bearing capacity of the gob; a pressure balance exists between the abutments and the gob (*40*). The result is high abutment stresses on the panel edges and ends, with a corresponding destressing of the gob. Figure 6*A* shows a hypothetical stress profile across a longwall gob, far removed from the panel ends. The actual stress profile depends on the abutment pillar stiffness, the panel width, the presence of massive beam-forming strata in the overburden, and the properties of the gob. Close to the abutments, a destressed zone usually exists where the vertical stress on the gob is less than original cover stress. The gob stress rises towards the panel center, possibly reaching original cover stress at three-tenths of the cover depth behind the longwall face, if the panel is wide enough (*40*).

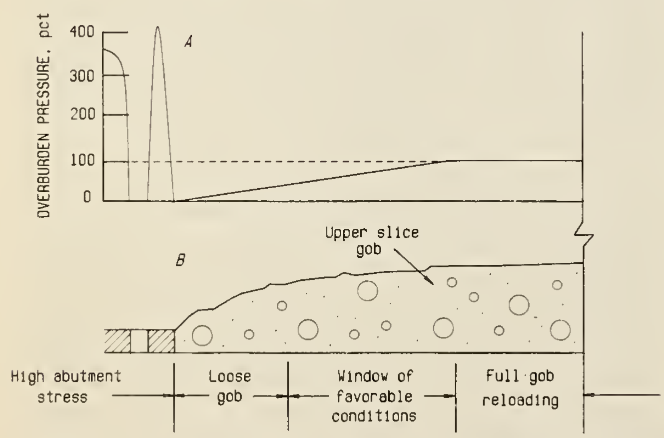


Figure 6.–Hypothetical location for lower slice mining. ***A*, Stress profile across upper slice gob; *B*, window of favorable conditions for lower slice workings.**

The shape and magnitude of the stress profile indicate a logical location for the lower slice longwall. Lower slice ground control conditions are likely to be better where vertical stress is reduced and worse in high stress zones. The destressed zone beneath the upper slice gob is likely a good location for lower slice development, whereas ground control problems might be expected beneath the highly stressed abutment zones on the panel edges. An additional consideration is the consolidation of the upper slice gob. Where stress on the gob is very low, the gob may not be consolidated, thus the destressed zone immediately next to the abutments is also a likely location to avoid placing lower slice development entries. Lower slice entries can be inset far enough from the gob edge to avoid this zone, but not so far as to reach the zone where full overburden pressure exists. Hypothetically, there exists a window of optimum destressing and gob consolidation conditions where lower slice development entries would be best located. The location and width of the window would depend on the upper slice gob stress profile, consolidation of the gob, and the capabilities of the development support system. Figure 6*B* shows the general location of the window that might be favorable for lower slice workings.

Insetting of lower slice entries from the edge of the upper slice gob has been practiced in the United Kingdom, U.S.S.R., China, and Japan. At the Daw Mill Mine in the United Kingdom, lower slice entries were offset (inset from upper slice entries) 4.5 to 14 m (*6, 41*). Upper slice single entries were supported by steel arches, whereas lower slice single entries were supported only with square-set supports and showed no evidence of weight. Lower slice gates (development entries) were offset from upper slice gates in the Kostenko Mine in the U.S.S.R. to minimize problems of strata interaction (*22*). In the U.S.S.R., a requirement for thick-seam mining is the location of lower slice workings under upper slice gob not more than 5 to 7 m from the edge of the upper slice pillars (*42*). Pillarless mining is a technique practiced in China to mine thick seams (*8*). One measure in pillarless mining taken to simplify gate maintenance is to locate the gate in a stress-relieved area (*9*). Japanese practice at several mines was to recess lower slice entries inside the upper slice entries to place them under gob (*4*). The strategy has the disadvantage that succeeding lower slices will become narrower and narrower, reducing recovery.

Other types of layouts have been suggested for the lower slice. Bise (*43*) suggested driving the lower slice gateroads outside the boundaries of the upper slice panel to place them beyond the zone of abutment pressure. This layout has the advantage of placing entry roof under undisturbed coal rather than under the possibly cracked floor of the upper slice panel. Wilson designed a lower slice layout for an existing thick-seam mine in Utah (*6*). Lower slice gateroads would be located beneath gob, but a crosscut passed beneath the upper slice gateroads and abutments to reach the adjacent lower slice. Mining beneath the upper slice abutment opens some layout options to mine designers, but if abutment pressures are high, it may not be

feasible. Individual designs will probably be needed for each thick-seam deposit, depending on site-specific parameters.

BENEFITS OF CONSOLIDATED GOB

Allowing time for consolidation of the upper slice gob can reduce the risk of the gob caving into lower slice development or longwall face workings. If the intermediate rock or coal band separating the slices was to become thin or to fail, upper slice gob might be directly exposed in the lower slice roof. Given sufficient time, overburden pressure, some water, and roof composition, the gob may regenerate as previously discussed. A reconsolidated gob will also aid in sealing off any spontaneous combustion heating that may have occurred in the upper slice gob. Thick western coal seams may be more prone to spontaneous combustion than thinner eastern seams. Mining underneath a spontaneous combustion heating in the upper slice gob would be extremely hazardous. Additionally, allowing time for gob consolidation will reduce interaction with adjacent longwall panels.

GEOLOGIC FACTORS AFFECTING MULTISLICE MINING

The geologic factors that affect development of multislice mining include many of the same factors that will affect the development of standard longwalls (*3*). Features that may affect development include the lithology of the roof and floor rock, the thickness of the coal seam, the presence, development, and composition of partings in the coal, the degree of development of cleats and joints, the presence of major and minor faults and fracture zones cutting the deposit, and the presence of undulations in the seam.

At present, no operations in the West are using the multislice mining method. Most of our knowledge has been derived from case studies of foreign operations. As such, the effects of these geologic factors on western thick seam development are theoretical, and will not be verified until the multislice method is used to mine western thick seam deposits.

The geologic factors that potentially affect multislice longwall mining can be categorized in three main divisions: (1) the factors that directly or indirectly limit the thickness of coal in the upper and lower slices; (2) the factors that decrease or otherwise affect the competency of the interburden left between the two slices; and (3) the factors that affect compaction of the gob.

FACTORS AFFECTING COAL SEAM THICKNESS

Thickness of a seam or of separate coal seams is an important consideration. During panel development, the minable thickness is determined by the mine plan and mining equipment used. A decrease in thickness below a minimum determined by the equipment limits the reserves accessible to the company unless rock is mined. The decrease can be an actual thickness loss where the seam either thins out abruptly, is faulted out, or is eroded. A reserve loss can also be caused by undulations in the seam or by partial displacement of the seam by faulting. This condition forces the equipment out of the coal and into the roof and floor rock.

In western coal, a seam can thin, thicken, or split over a short distance. A representative example of this can be found in Collins (*44*) in the discussion of the Coal Basin Coalbed of the Carbondale Coalfield, western Colorado:

> "In the Bear Creek area (Sec 21,T.10 S,R.89 W) four distinct beds are present, from bottom to top 2 feet, 3 feet, 2 feet, and 10 feet thick, separated by partings 5 feet, 1 foot, and 1 foot respectively. In the 4th North entry of the L.S. Wood mine (SW 1/4 Sec. 8), a single seam approximately 25 feet thick is present, while less than one-half mile north, along the south fork of Coal Creek, three beds appear, 3 feet, 6 feet, and 8 to 10 feet thick, separated by partings 3 to 4 feet and 4 to 6 feet in thickness. West of the old Coal Basin townsite, the seam again appears as a single bed approximately 30 feet thick."

From maps given in the report, the linear distance represented in the discussion was estimated to be approximately 4 miles. By written communication from the author, an error in the original paper reports the thickness of the coal to be 35 ft. The correct thickness is 25 ft.

The thickness and any changes in thickness are often the direct result of the deposition of the coal environment. During initial peat accumulation, the sedimentation processes dominant during deposition affect the final form of the deposit. These processes that control the thickness and change in thickness are discussed in detail in the work of Ryer (*45*), Lawrence (*46*), and Flores (*47*).

FACTORS AFFECTING COMPETENCY OF INTERBURDEN

The interburden is the material, either rock or coal, that separates the upper and lower slices. It acts as the roof for the developing lower slice and separates the upper slice gob from the lower face. For this reason, the strength of the plate of rock or coal making up the interburden is critical to the success of a multislice operation.

The interburden may also act as a seal, preventing gas, water, and finer material from moving between the different slices. The low permeability may prevent air leakage between the two panels, decreasing the potential of developing spontaneous combustion in the gob or fractured coal in the two slices.

Factors that will affect the stability of the interburden include its thickness and lithology. These, in part, will determine the strength of the material separating the two slices. Both thickness and lithology can vary significantly in a short distance across a panel, resulting in variations in the strength and stability of the plate at different places along the face.

Along with the above, the presence, development, and continuity of bedding planes, cleats, joints, and fractures are also important. These may adversely affect the strength of the interburden by acting as potential planes of failure. They may also act as conduits, allowing gas and water to move between the two slices. These factors can also change over a short distance.

FACTORS THAT AFFECT COMPACTION

The gob, how well it compacts, and how long it takes to compact are important considerations in multislice mining for several reasons. First, if the gob in the upper panel is well consolidated, then a roof fall initiating in the split is less likely to propagate into the gob. Any breaks that propagate through the interburden would allow unconsolidated material to cave into the lower workings. Like the interburden, the consolidated gob material may form a barrier, limiting the transfer of gas, water, and ventilation air between the two panels. Finally, the time factor is important, especially in nonsimultaneous mining where extraction of the lower panel is dependent on compaction of the gob from the upper panel.

Several of the major geologic factors that are hypothesized to control gob compaction are lithology of the roof and interburden, presence of bedding planes and abrupt changes in lithology, joints and fractures, and water.

Lithologic Composition of Roof and Interburden

The lithology of the roof of the upper slice and the interburden between the two slices affects the compactability of the gob for both the upper and lower panels. The lithology often varies significantly, both vertically and laterally. As the lithology is an important factor determining the strength of the roof and split, it will also determine the strength of individual blocks that makeup the gob. Ultimately, the lithology will be a main factor in determining the characteristics of the gob, including its compactibility.

Bedding Planes and Abrupt Lithologic Changes

Bedding planes and surfaces of lithologic change (such as an erosional surface) can often act as planes of separation and failure during caving. As such, the number and degree of development of these horizontal to low angle features are important. The spacing between the more well-developed bedding planes in many cases may equal the smallest dimension of the gob block.

Joints and Fractures

As joints and fractures also represent surfaces of potential failure, their continuity and spacing are important in determining the size and shape of individual gob blocks.

Water

Water may aid in the compaction process. In the presence of water, some argillaceous roofs may consolidate more readily, requiring less time for compaction (*23*). Yet, too much water may actually decrease stability of the consolidated roof (*34*). Water also has been known to collect in mined out areas in the upper slice, eventually rushing into the lower working face and creating an extreme hazard.

In summary, the geologic factors that affect multislice mining are those that affect the minable thickness of the coal, the strength and permeability of the interburden separating the two slices, and the strength and compactibility of the gob. In any given depositional environment, these features can change within a short distance. Given this, the conditions on the face can also change quickly. Predicting the effects of these factors on panel layout and development in a multislice operation requires careful mapping of both the lithology and structure of the coal-bearing section.

MULTISLICE MINING AT DUTCH CREEK MINE

A joint Bureau-industry test of multislice longwall (*37*) is planned at the Dutch Creek Mine (formerly Dutch Creek No. 1 and No. 2), operated and owned by Mid-Continent Resources, Inc., near Redstone, Colorado (fig. 7). The mine extracts high-grade metallurgical coal from two seams separated by about 500 ft. Multislice mining is planned in the lower of these two seams, which is split into two sections by a rock parting approximately 10 ft thick. Only the upper section, designated the B bed, is now mined. Lower slice mining is planned in the A bed, underneath the rock parting.

DUTCH CREEK MULTISLICE LAYOUT

The upper slice, a longwall panel designated LW102 (fig. 8), is an 800-ft-wide advancing longwall utilizing monolithic pack wall supported double-entry head-tail entries (*36*). The lower slice will use a two-entry development system inset approximately 60 ft inside the upper slice pack walls on both sides. Double entry was picked for the lower slice because it has no four-way intersections that might increase roof problems, and because it provides better recovery than a three-entry system. Unlike the upper slice, the lower slice will use retreating longwall, requiring full development prior to mining. Retreat longwall will permit probing lower slice ground control conditions and blocking out of the panel prior to committing the longwall face equipment. The lower panel width will be 510 ft, giving a combined upper and lower slice recovery of approximately 68 pct.

Access to the lower bed will be by a ramp in the existing upper slice head-tail entries. After the ramp has reached the lower bed, development entries will pass under upper slice gob until the required 60-ft inset is obtained. Development entries are not planned to be driven through or underneath the upper slice barrier because it is highly stressed from upper slice mining and might bump. The high stress would also cause severe ground control problems while driving through the barrier, especially near the edge of the pillar.

GEOLOGY - DUTCH CREEK MINE

The Mid-Continent Dutch Creek Mine is located in the Coal Basin area of the Carbondale Coalfield on the southeastern edge of the Piceance Basin in Pitkin County, CO (fig. 7). The mine produces high quality metallurgical coal from the Upper Cretaceous Williams Fork Formation of the Mesaverde Group.

The coal-bearing strata outcrop in the Coal Basin Anticline, a predominate structure in the area. The anticline, a large-scale fold plunging to the northwest, was believed to have been formed by doming over a small laccolithic intrusion (*48*). The structure has been deeply eroded, exposing the Williams Fork Formation. At the mine, the strata strike north-northwest and dip approximately 11° to 13° to the southwest (*49*).

The Mesaverde Group consists of the Iles and Williams Fork Formations. The Iles Formation contains the tongue of Mancos Shale and the Rollins Sandstone Member at the top (*44*). The Williams Fork Formation is divided into the Bowie Shale Member, the Paonia Shale Member, and an undifferentiated unit. The coal seams of greatest economic importance are from the Bowie Shale Member. The Coal Basin A and B seams (referred to as the A and B seams hereafter) are located at the base of the Bowie Shale directly above the Rollins Sandstone Member.

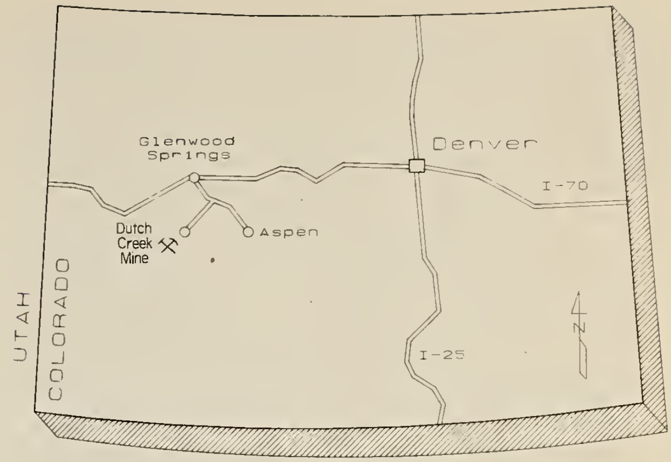


Figure 7.–Location map of planned multislice trial in western coal seam.

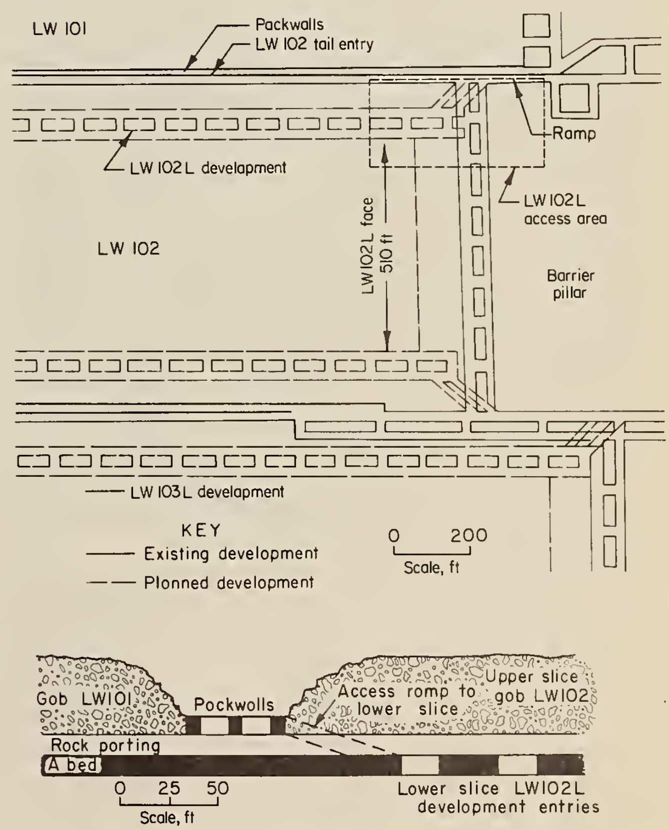


Figure 8.–Layout of planned multislice trial. *A*, Map view; *B*, cross section of access area parallel to longwall face.

The coals of the Coal Basin area have been described by Collins (*48*) as being deposited generally in fresh-water swamps. They are made up primarily of the remains of woody plants. The coal in the study area has been upgraded to medium volatile bituminous in rank. Although the coal measures have been cut by a number of dikes and sills, their presence is not believed responsible for the increase in rank of the coal. Instead, heat from the laccolith is believed to be responsible for upgrading the coal.

At present, there is a limited amount of published information available on the geology of the Dutch Creek Mine. The following discussion was derived from Collins (*44, 48*), Bigarella (*50*), and from work and observations of Bureau staff. A number of geologic factors will be important in determining the success of a multislice operation at the Dutch Creek Mine. These are variation in thickness of the A and B coal seams, variation in thickness of the split separating the two seams, and lithologic variation in the roof, floor, and interburden between the two seams. The presence of cleats, joints, and fractures are also important. The frequency and degree of development of joints and fractures in the interburden rock will determine the strength and permeability of the material separating the two slices.

Figure 9 is a composite log of core taken in the roof and floor of the B seam; the core was taken in the headgate entry of the panel being analyzed (panel LW102). Seam thickness at the panels is approximately 10 ft for both the A and B seam. The thicknesses of the seams are not believed to change rapidly in the study area, minimizing the potential for problems due to thinning of the seam below the limit set by equipment. The interburden was reported to vary from 4 to 12 ft thick in the mine. In the study area, the interburden is approximately 10 ft thick (fig. 9). The face appearance of the coal in the Coal Basin area is variable (*50*). The coal can be blocky, shattered, and any degree in between the two. The Coal Basin Seam was reported to often be uncleated. Yet, after failure during testing, visually uncleated samples showed development of two cleat sets. Observations in the mine show that the coal is not really uncleated, but it has been masked by subsequent fracturing and shearing in numerous directions related to tectonic activity (51).

The lithology of the roof, parting, and floor rock is variable (*52*). The predominant lithologies present are sandstone, siltstone, mudstone, and coal. From figure 9, the immediate roof of the coal deposit consists of siltstone and black shale, coarsening upward into light gray sandstone. Above the sandstone, the roof is made up of shale, with minor amounts of sandstone and clay. Upon observation, the immediate roof appears highly competent, with bed separation similar to that of slate. Few fractures were noted in the roof.

The floor of the A seam is made up of shale, carbonaceous shale, and siltstone. In the core taken at the study area, the separation between the A seam and the underlying Rollins Sandstone is approximately 7 ft thick (fig. 9). This sandstone unit has in the past been a source of both water and gas that has migrated into the upper slice workings. Development of the lower slice in the A seam is not expected to present a problem because of the degassification caused by mining of the upper slice.

The parting separating the A and B seams is critical as it is the floor of the upper slice and the roof of the lower slice. At the study area, the parting was made up of black silty or carbonaceous shale with coal streaks, silty sandstone, and interbedded sandstone and shale (fig. 9). A section of the interburden was exposed due to heave along the tail entry of one of the panels. The exposure consisted predominately of thin-bedded sandstone interlayered with shale. Bedding planes were common and closely spaced in both the core and exposure of the parting.

Jointing and fracturing of the rock was common in the core. Most of these planes of weakness were found in the interburden. The core was cut by a number of high angle to vertical fractures in the parting rock. It is not known if these fractures were naturally occurring or the result of heave.

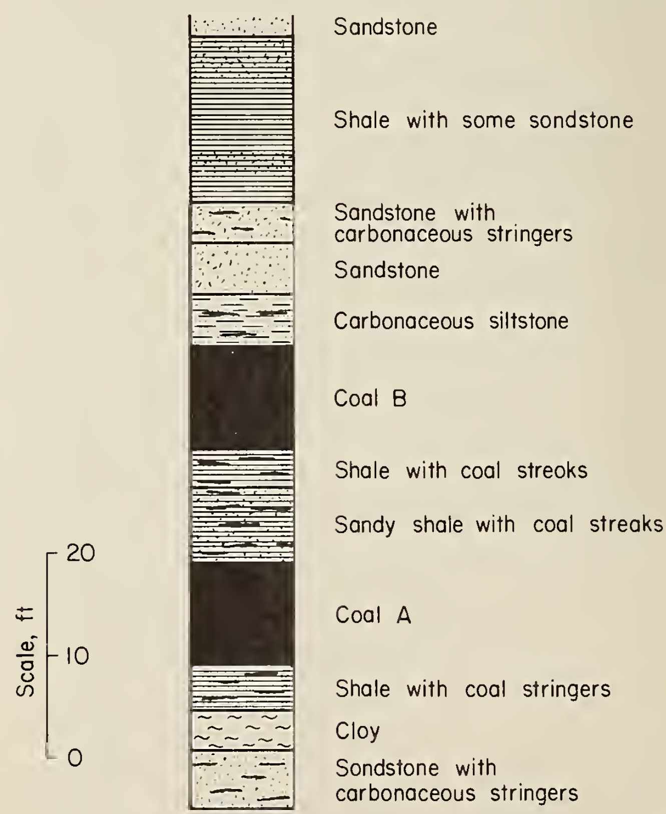


Figure 9.–Geologic column of multislice trial area.

The geologic factors that will affect the success of multislice mining in the study area are those that will affect either the strength of the interburden between Coal Basin A and B seams or the compaction of the gob. We do not know how the lithology and relative strength of the interburden vary across the panels. But, if the core section is representative of the characteristics of the split over the lower panel, the strength of the interburden between the two seams could be decreased because of closely spaced bedding planes and high angle to vertical fractures present in the strata.

Due to the competency of the roof rock making up the individual gob blocks, the upper slice gob is not expected to compact readily. It may take several years to consolidate.

STRUCTURAL ANALYSIS OF PLANNED MULTISLICE SITE

A simplified two-dimensional plane strain finite element analysis of the multislice trial site was made to estimate the stress profile across the site upper slice panels. The computer program Automatic Dynamic Incremental Non-Linear Analysis (ADINA) (*52*) was used for the analyses. ADINA was selected because of its capability to model the complex longwall and pack wall geometries and to model formation of pack walls through the birth-death procedure. The determined shape and magnitude of the stress profiles indicate the premining stress environment for the lower slice and can aid in locating lower slice head-tail entries.

Some computer model input parameters were simplified to reduce costs and provide conservative estimates. The seam was modeled as flat rather than at the actual 10° dip. A uniform depth slightly in excess of the actual overburden thickness was input. A single gob modulus was used for the entire gob rather than dividing the gob into zones of different moduli as done by other researchers (*53*). A previous analysis (*5*) using the model showed that the upper slice gob modulus input into the model determined the amount of gob destressing and the abutment stresses. A final estimate of 60,000 psi was made for the gob modulus and the results reported herein for that input.

The finite-element mesh (fig. 10) modeled a vertical section parallel to the longwall face far removed from the face ends. The model incorporates the upper and lower sections of the coal seam, each 10 ft thick, and the 10-ft rock interburden. The cover depth is 3,000 ft, and the widths of the pack walls, entries, and two adjacent longwalls designated LW101 and LW102 are 7, 16, 550, and 800 ft, respectively. The mechanical properties of the coal, rock split, pack walls, and roof-floor strata are summarized in table 1. The materials modeled are assumed to be linear-elastic and isotropic. The mesh consists of 1,760 nodes and 1,700 quadrilateral elements, and is 2,700 ft wide by 5,900 ft high.

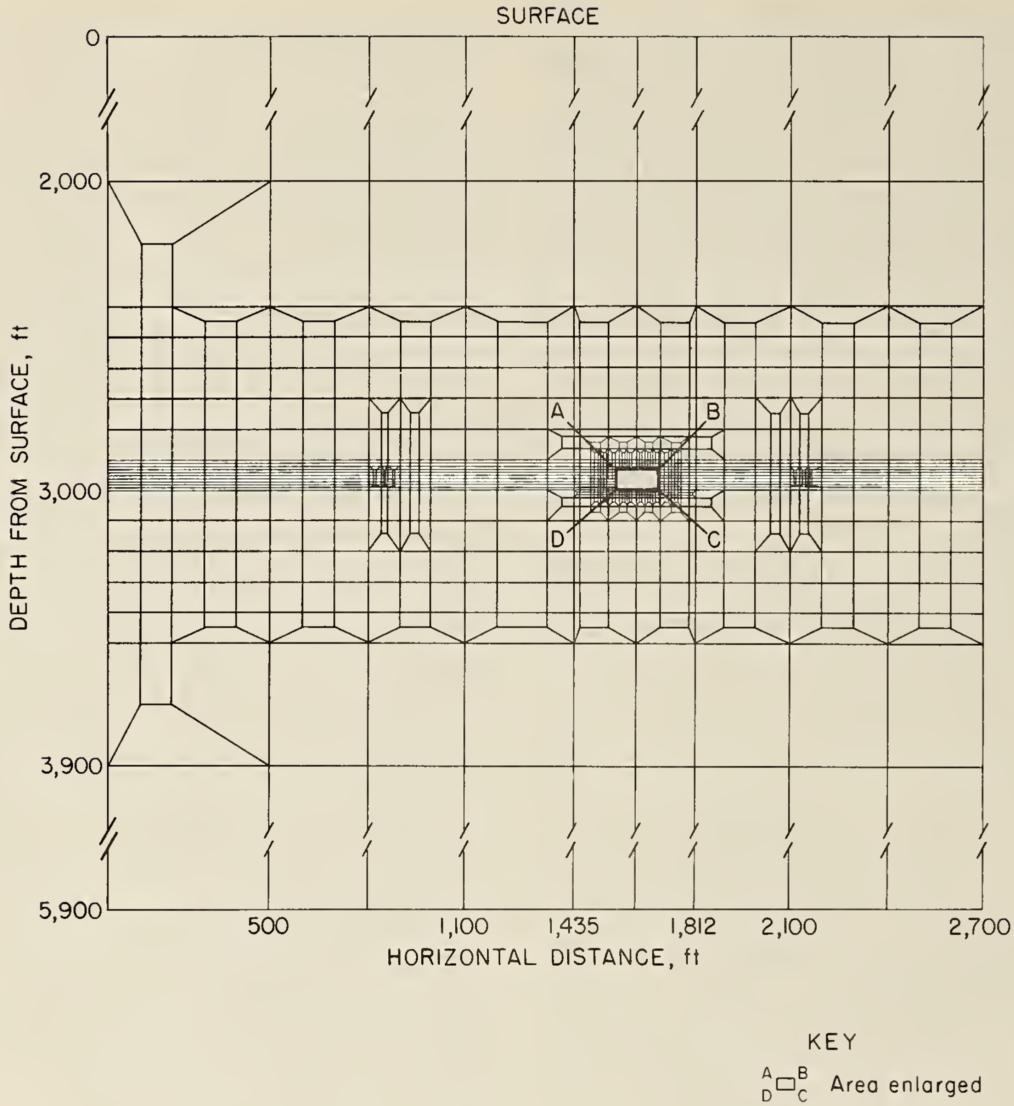
The element birth-death option available in ADINA was used to simulate panel extraction and the subsequent formation of gob. This feature enables the user to activate-deactivate designated groups of elements. The geometry of the gob zone was defined to allow the birth-death option to operate on the elements within the gob boundaries. The upper limit of the gob zone is controlled by the caving height (the height to which block-forming fractures propagate into the immediate roof), and is assumed to be four times the seam height (fig. 11). The caving height was assumed to be four times the seam height because the Mid-Continent roof is known to break into large blocky fragments, which would probably give a low-bulk factor (the ratio, volume of gob to volume of original roof rock) (about 1.25). A bulk factor of 1.25 would produce a caving height of four times seam height. Initially, the elements within the specified boundaries represent the coal seam and immediate roof. To simulate excavation, the gob zone elements are deactivated (death), and are then assigned assumed gob properties and reactivated (birth), simulating the gob.

Table 1.–Finite element model physical properties

Layer	Rock type	Compressive strength, psi	Composite Young's moduli, 10^6 psi	Composite Poisson's ratio
Roof:				
Upper	Siltstone-sandstone	19,897-29,610	3.523	0.182
Middle	.. do	15,774-23,799	3.771	.208
Lower	Fine sandstone	24,767	3.440	.189
B seam	Coal	1,771- 6,147	[1].476	.32
Pack wall	Concrete	4,108- 6,847	[2].253	.13
Rock parting	Siltstone-sandstone	5,867-32,931	3.039	.185
A seam	Coal	1,615- 3,343	[1].526	.32
A seam floor	Shale-coarse sandstone	4,068-22,962	1.209	.203

[1]Average.
[2]Not composite, 10 pct of average modulus of 2.529 x 10^6 psi.

NOTE.–Physical properties were determined from uniaxial compression tests of cores.



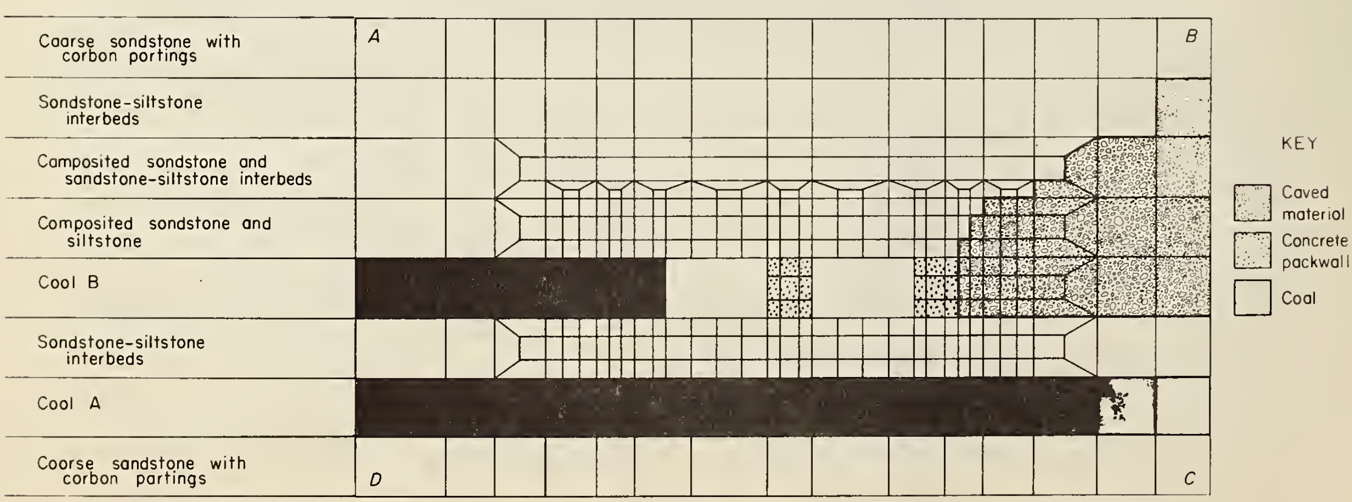


Figure 10.–Finite element mesh of multislice trial. *A*, **Global mesh;** *B*, **detailed mesh.**

Figure 11 shows the stress profile across the two panels (LW 101 and LW 102) for one and two panel extraction. The second panel modeled (LW 102) is the site of the planned multislice mining. The initial overburden stress of 3,300 psi is shown for reference. After extraction of one panel, the abutment stress on the pack walls between the panels is approximately doubled. The stress on the mined out panel is only 33 pct of the original cover load. After extraction of two panels, the abutment stress rises from four to five times cover stress, and the stress on the second panel (LW 102) gob, which is to be the upper slice, is about 43 pct of the cover stress.

The model indicates that the vertical stress on the lower slice (LW102L) will be substantially less than the cover stress of 3,300 psi. The planned 60-ft inset should locate the lower slice development entries sufficiently far from the upper slice pack walls to avoid the high stress concentration on the pack walls. The development of lower slice entries underneath upper slice head-tail entries as proposed for another site (*6*), probably would not be practical at the Dutch Creek site.

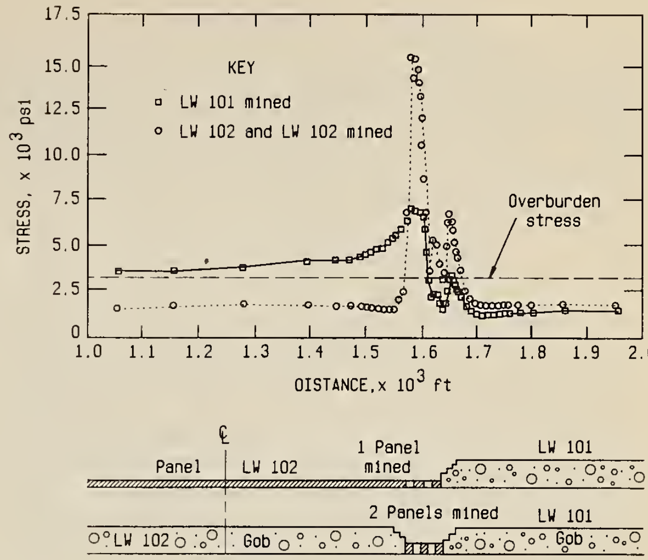


Figure 11.–Computed stress profiles of multislice trial.

COST ANALYSIS OF MULTISLICE MINING

U.S. coal markets are highly competitive. Western thick seams are frequently far removed from their market destinations, and rail costs are high. Thus, multislice mining costs should be as low as possible. Using an intermediate rock parting for lower slice roof, as planned at the Dutch Creek multislice trial, appears to offer good potential to keep costs low at this time. As improvements are made in multislice technology, other methods, such as using artificial roof, may become cost competitive.

Besides direct costs like labor and material, mine operating costs also depend on layout, ground control conditions, and advance and retreat rates. Different productivities are achieved by development and longwall mining, which in turn affects the total cost of the coal mined. One strategy to reduce cost is to minimize the amount of development work relative to longwall mining by making longwall panels wider. As will be shown later, wider panels also increase overall coal recovery.

A computer model was used to estimate the effect layout and ground control conditions might have on multislice mining using typical western entry systems and an intermediate rock parting as a lower slice roof. The objectives were to compare relative costs of different development systems and estimate the sensitivity of costs to layout geometry, ground control conditions, and in situ variables, such as seam and rock parting thickness. A determination of selling price, discounted cash flow, or rate of return was not intended.

DESCRIPTION OF COMPUTER MODEL

The model was developed using Lotus 1-2-3 on an IBM[6] XT computer. Lotus, in addition to its spreadsheet application, allows the user to easily program mine relationships.

DESCRIPTION OF HYPOTHETICAL MULTISLICE CASES

This study analyzes two hypothetical cases of multislice mining in order to estimate direct operating costs. The cases are derived along the lines of reference (*4*). The associated productivities and resource recoveries are also estimated.

Multislice mining has not been used in the United States, so actual geotechnical conditions have not yet been experienced. In order to build the cost models, some basic assumptions were made. These assumptions are explained in detail below. Sensitivity analysis was used to determine how sensitive the results are to particular assumptions.

[6]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

PHYSICAL ENVIRONMENT

The physical environment is common to each of the two cases. The underground mine is in the western United States and has a level thick coal seam that is split in two by a rock parting. The upper and lower splits are each 10 ft thick, and the parting is also 10 ft thick.

MINING METHOD AND PLAN

The upper split is mined first, and, some years later, the lower split is mined. The mining method for both the upper and lower splits is longwall production with continuous miner development. In both cases, the upper seam longwall is 800 ft wide. Lower seam panels are developed within the perimeter of the upper seam panels, offset 60 ft inside any upper seam chain or barrier pillars. Two-entry development is used (figs. 12-13). Bleeders are driven in the upper split, but not in the lower split. Tables 2 and 3 summarize the cost model assumptions.

In case 1 (fig. 12), the upper split is developed by one 3-entry continuous miner section, which develops the gate entries, bleeder entries, and starting rooms. The lower split is developed by two sections, one from the tailgate side and one from the headgate side. Each section drives a pair of decline tunnels from the upper split mains to gain access to the lower split. Once the lower split is intersected, the entries are driven, as shown in figure 12. Two lower slice development sections are required because both the headgate and tailgate entries must be driven for each panel. Only one set of tunnels must be driven for each panel, however.

In case 2 (fig. 13), one 2-entry section develops the upper split. The lower split is reached, as in case 1, by two parallel declines from the upper split mains. After the declines intersect the lower split, two gate entries are driven so that each is outside the upper seam entries. Crosscuts are at 200-ft centers, aligned under the upper split crosscuts. Because of the long, widely spaced crosscuts, development is slow. Therefore, to keep up with the lower split longwall retreat, two panels are always being developed simultaneously.

RESULTS OF ANALYSES

Table 4 shows the major results for both cases for the assumptions in tables 2 and 3. The average unit cost for case 2 is 8 pct higher than case 1's cost. The case 2 cost is higher largely because the lower split longwall must wait 7 months before development is finished. The slow development results from the widely spaced entries and the associated long crosscuts and the fact that only one section can be used in such a development configuration. The slow development causes the succeeding longwall to wait 8 months before it can move into the panel. When a longwall waits on development, it must pay for labor during the wait time.

In that case 2's unit cost is higher than that of case 1, one would expect case 2's productivity to be lower, and this is so. The main reason is the wasted labor caused by the waiting of the case 2 lower split longwall on development to finish.

Total combined development and longwall production in both cases is within 2 pct. However, keep in mind that case 2 develops the upper seam with two entries and case 1 develops with three entries. If case 2 had developed with three entries, both upper seam productions would have been identical. Case 2's lost tonnage will be picked up on the next panel.

Case 2 requires about 30 pct longer than case 1 to develop the lower split. As mentioned above, the difference is directly related to the slow development rate assumed for the widely spaced two-entry development method. If the longwall did not have to wait this additional time, it would mine out the panel in 12.9 months instead of 21.6 months.

Table 2.–Cost assumptions common to case 1 and case 2

Mining height, ft:		Operating shifts per day:	
Coal-longwall	10	Development	3
Development	8	Longwall	2
Interburden thickness ft	10	Annual salary costs:	
Specific gravity, lb/ft^3:		Laborer	$27,000
Coal	82	Salaried	$33,000
Rock	150	Fringe pct of annual wage	40
Workdays per year	225	Material and maintenance cost per short ton:[1]	
Average shearer tram speed, cycle ft/min	20	Development	$6
Average turnaround time min	7	Longwall	$4
Rock tunnel decline pct	10	Rock tunnel	$12

[1]Includes power, supplies, and parts; no labor is included. Development and longwall estimates were derived from an operating longwall mine. Rock tunnel costs were estimated at twice those of development work.

Table 3.–Separate cost assumptions for case 1 and case 2

	Case 1		Case 2	
	Upper Split	Lower Split[1]	Upper Split	Lower Split[1]
Longwall face length . . . ft . .	800	584	800	602
Outby barrier . . . . ft . .	400	460	400	460
Inby barrier . . . . ft . .	400	NAp	400	NAp
Development entries	3	2	2	2
Entry centers . . . . ft . .	60	48	60	180
Entry width . . . . ft . .	18	18	18	18
Crosscut centers . . . . . . ft . .	100	100	100	200
Starting rooms	2	2	2	2
Crew sizes:				
Development, per shift:				
Laborer	8	7	7	7
Salaried	1	1	1	1
Longwall, per shift:				
Laborer	9	8	9	8
Salaried	1	1	1	1
Special crews-per day:				
Laborer	8	8	8	12
Salaried	2	2	2	3
Material difficulty factor:[2]				
Development	1.0	1.3	1.0	1.5
Longwall	1.0	1.2	1.0	1.2
Panel advance, ft per month per shift:				
Development[3]	160	176	176	50
Longwall[4]	150	195	150	190

NAp Not applicable.

[1]Lower split face length is determined from the geometry of the upper and lower splits.

[2]Used to increase material and maintenance costs per short ton because of poorer geotechnical conditions in the lower split. Material and maintenance costs are multiplied by this factor to obtain lower split costs.

[3]Basic panel advance rate for a 3-entry system was set at 160 ft per month per shift. This rate is increased by 10 pct when 2-entry development is used. Rate for case 2 in lower split was estimated taking into account the long crosscuts that may exacerbate ventilation problems and which will increase average tramming times.

[4]Upper seam retreat rate was assumed at 150 ft per month per shift. Lower seam face length is shorter because it is set in from the upper split entries. At the same tram speed and turnaround time end time, lower split retreat rate is mathematically faster than upper split longwall.

Table 4–Cost analysis results for case 1 and case 2

	Case 1	Case 2		Case 1	Case 2
Cost per short ton:			Time, months:		
Average[1]	7.72	8.12	Upper split:		
Upper split	6.78	6.64	Development and access . .	17.8	16.3
Lower split	8.77	10.48	Longwall	18.8	18.8
Productivity, st/employee-shift:			Lower Split:		
Average	58.94	48.41	Development and access . .	14.3	20.8
Upper split	68.17	73.16	Longwall	15.1	21.6
Lower split	49.72	33.17	Resource Recovery, pct:		
Production, st:			Total	68.0	70.9
Total	3,135,450	3,060,750	Upper split	78.6	81.6
Upper split	1,813,081	1,762,330	Lower split	57.3	60.1
Lower split	1,322,369	1,298,419	Upper split portion of total . . .	39.3	40.8

[1]Average, weighted by tonnage, of the upper and the lower split costs.

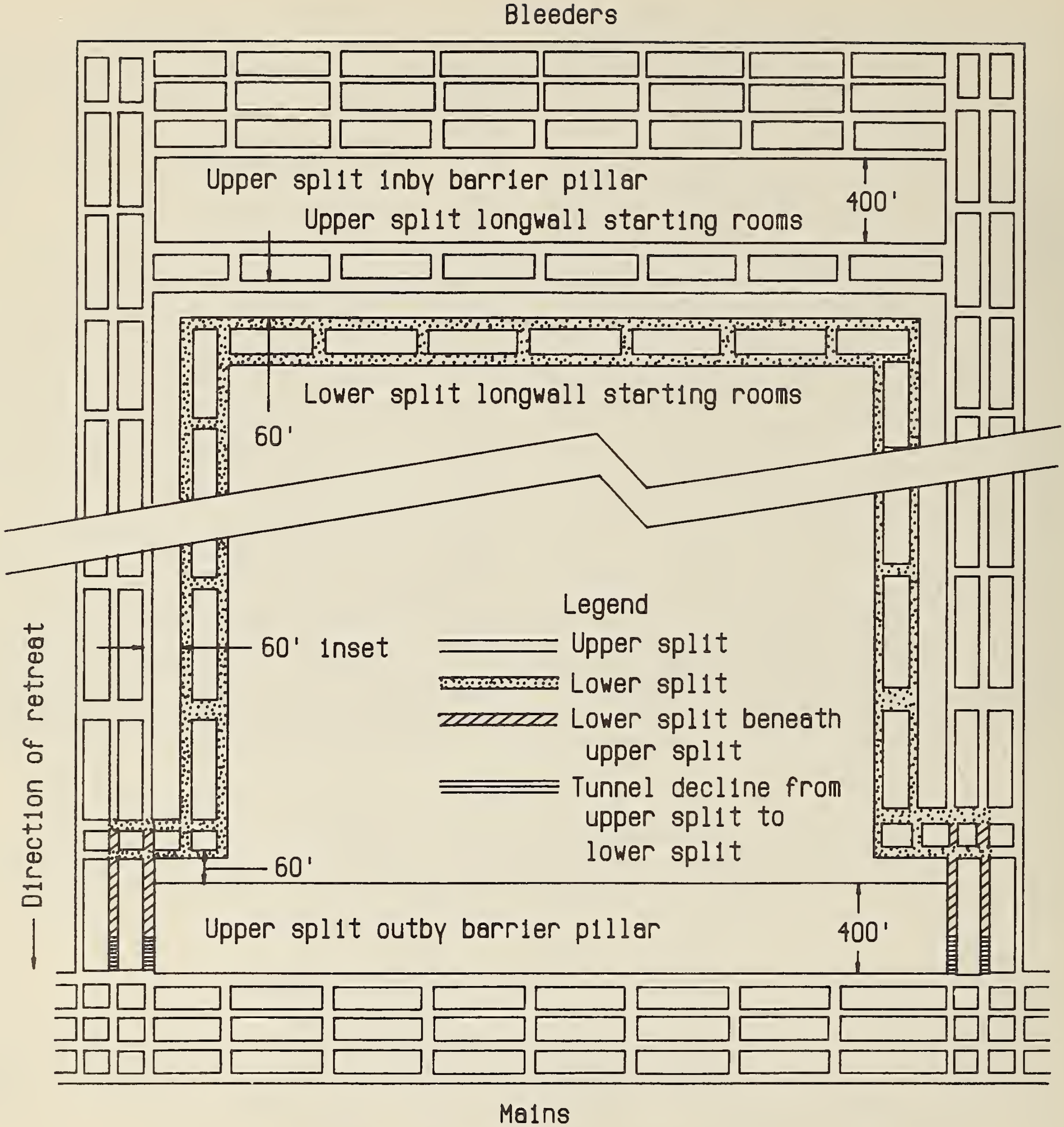


Figure 12.–Case 1 multislice development layout.

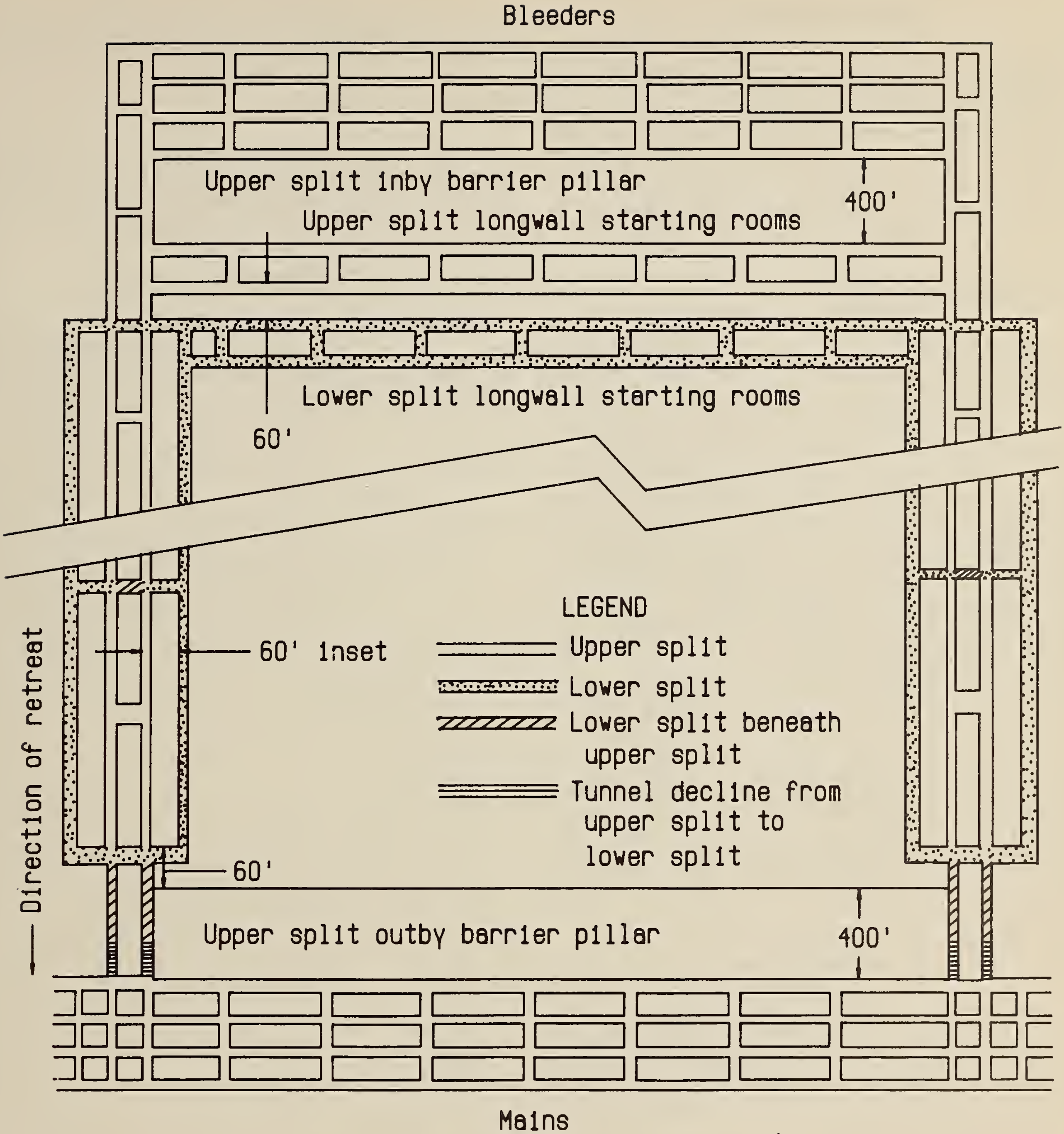


Figure 13.–Case 2 multislice development layout.

Sensitivity Analysis

Many factors can affect operating costs. The model examined the cost effects of multislice layout dimensions, development entry type, development and retreat rates, and the difficulty of mining. Each of these factors was varied in the model to determine the sensitivity of costs to the factor.

Cost is the direct operating cost and includes both development and longwall costs. Six cost sensitivities were run.

Upper Split Face Length

Figure 14 shows that, as the upper split face length decreases, lower split costs rise faster than upper split costs. The lower split longwall face length is a function of the development geometry, the inset, and the upper split longwall face length. As the upper split face length decreases, the lower split face length decreases foot for foot. Percentagewise, the lower split face shrinks faster. As face length shrinks, gate entry development stays constant; the only development saved is the starting rooms are shorter by the exact amount of the face shrinkage. Therefore, the time required for the longwall to mine a panel shrinks faster than the time to develop a panel; hence, as the upper seam face reduces, the lower seam longwall must wait longer on development.

Number of Upper Split Development Entries

Figure 15 shows that as the number of upper split development entries increases, costs rise. Upper split costs rise because each additional entry requires more labor and material and, most importantly, more time. Hence, the upper split longwall is more likely to wait longer on development as the number of entries increases. Lower split costs are unaffected.

Upper Split Longwall Retreat Rate

Figure 16 shows that the cost benefit of a faster upper split longwall retreat rate has a limit. The cost improvement levels out quickly at the point where the retreat rate is so fast that development cannot keep up. As soon as the longwall must wait on development, there is no benefit to having a speedier longwall.

Material-Maintenance Factors

Figure 17 shows the effect of the material-maintenance factors, which are used to adjust development and longwall costs for difficult conditions in the lower split relative to the upper split. For example, if the user believes the lower split development and longwall will experience poorer ground conditions than in the upper seam, requiring more roof bolts, the user can insert a factor by which lower split material-maintenance costs are increased from those in the upper split. Longwall factors increase total unit costs faster than development factors because material-maintenance costs are a higher percentage in the longwall costs than in development costs.

Interburden Thickness

Figure 18 shows that interburden thickness plays a small role in the cost of the model. The only effect that interburden has in the model is its effect on the access tunnel length between the upper and lower splits.

Case 2 Lower Split Development Rate

This case was run because the assumed development rate was so slow (50 ft per month per shift, table 3). Figure 19 shows that should development speed increase, the total cost would decrease.

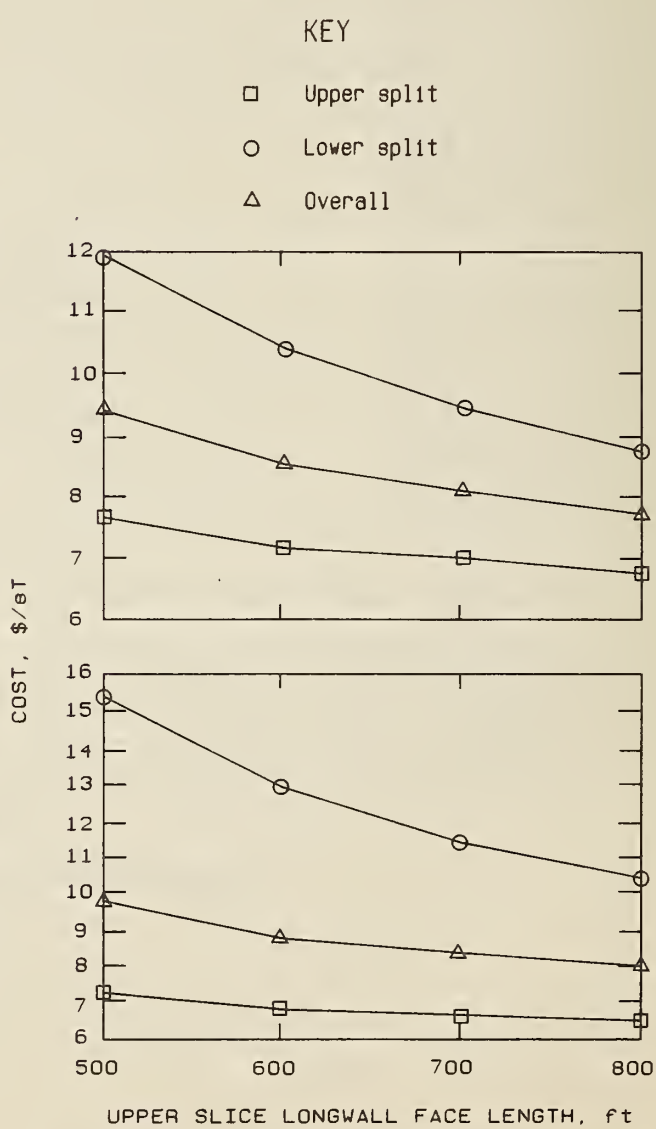


Figure 14.–Costs versus upper slice face length, case 1 (upper) and case 2 (lower).

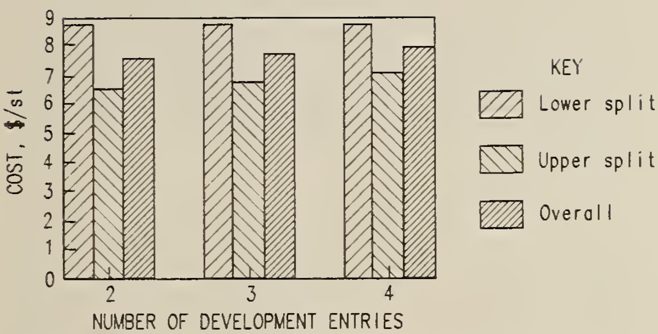


Figure 15.–Cost versus number development entries for case 1.

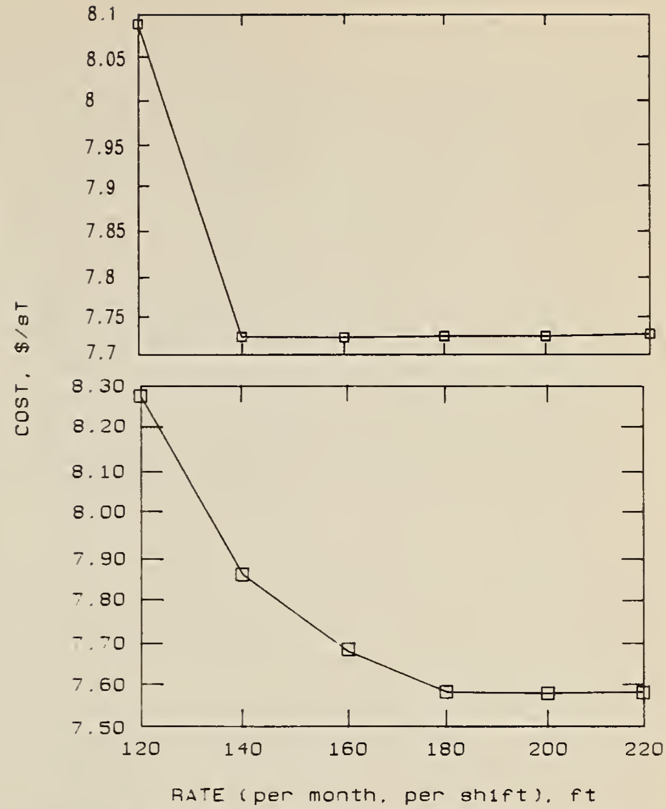


Figure 16.–Cost versus longwall retreat rate, case 1 (upper) and case 2 (lower).

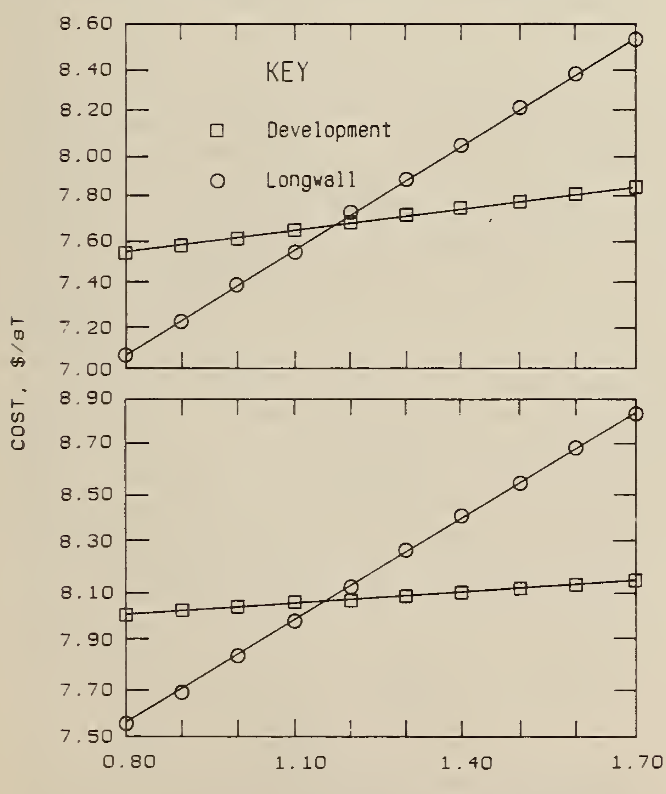


Figure 17.–Cost versus material-maintenance factor, case 1 (upper) and case 2 (lower).

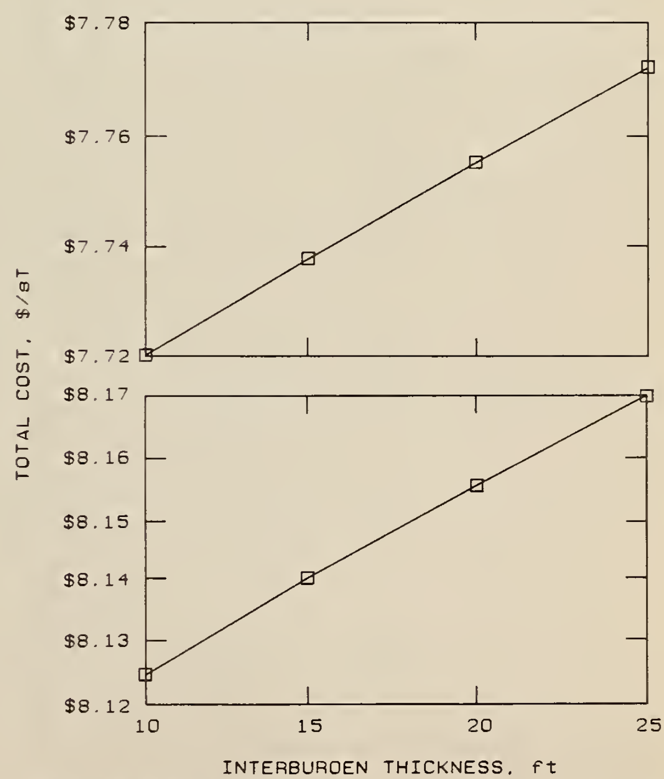


Figure 18.–Cost versus thickness of intermediate rock parting, case 1 (upper) and case 2 (lower).

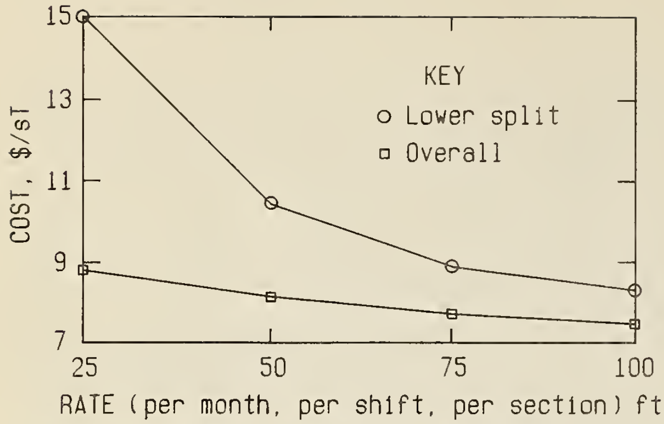


Figure 19.–Cost versus lower slice development rate for case 2.

Productivity

Productivity is closely related to the inverse of costs. Figure 20 shows the relationship between the upper seam face length and overall productivity. As face length increases, productivity increases. The change in slope between 600 and 700 ft is caused because the model added operating and maintenance people to a face when its length exceeded 650 ft, causing a step function to occur.

Resources Recovery

Mining of the lower slice in case 1 increased the coal recovered from 39.3 pct (upper slice mining only) to 68 pct of the total, using an 800-ft-wide upper slice panel. In case 2, recovery was increased from 40.8 to 70.9 pct. The case 2 recovery is slightly higher because fewer chain pillars are left behind. Figure 21 shows that total recovery from both upper slice and lower slice mining increases as much as 10 pct when the upper slice panel is widened from 500 to 800 ft.

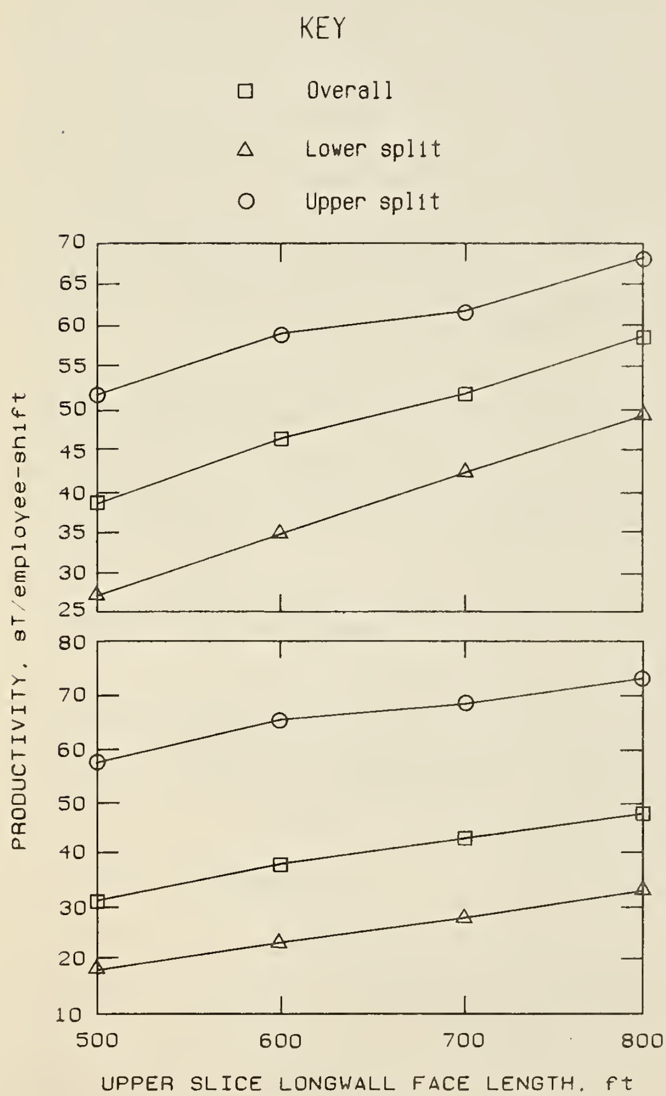


Figure 20.–Productivity versus upper slice face length, case 1 (upper) and case 2 (lower).

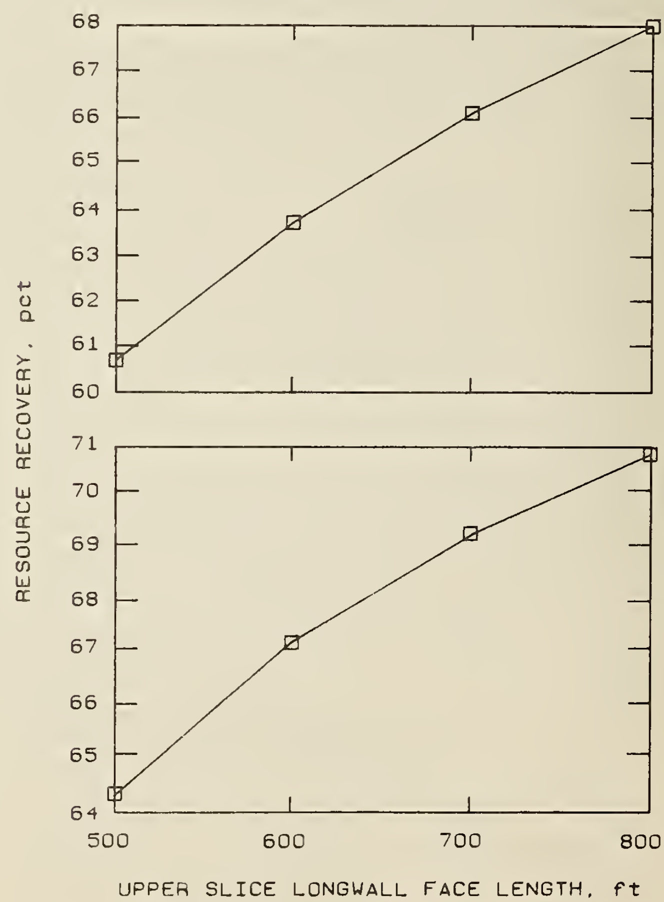


Figure 21.–Resource recovery versus upper slice face length, case 1 (upper) and case 2 (lower).

SUMMARY AND CONCLUSIONS

Multislice methods of mining coal are not now used in the United States, but are used, or have been used, in at least 13 countries throughout the world. These methods were researched to determine their layout and conditions under which they are applied. Ascending multislice is used in thick, pitching seams, usually with stowing material (backfill) to support the undercut roof. Descending methods are used in flatter seams. As many as 10 consecutive underlying slices have been mined in China. Longwall is most commonly used, but a room-and-pillar multislice method has been tested in Australia.

The geologic, ground control, and cost problems of applying multislice mining in the United States were analyzed, and the method appears to be feasible for extracting thick western coal seams. Standard longwall mining techniques can probably be used. U.S. safety, economic, and legal requirements will dictate the actual usefulness of the method. Safety requirements relating to ground control were discussed in this report. Spontaneous combustion is an additional safety problem that must be addressed if susceptible seams are mined. Highly competitive American coal markets require that lower slices have operating costs within the cost range of standard longwall mining. To satisfy U. S. legal requirements, standard American longwall development practice is needed. Further conclusions are presented under the headings of multislice methods, ground control, geology, and cost.

MULTISLICE MINING METHODS

The multislice method, believed by the authors to be best adapted to western thick seams, is nonsimultaneous descending longwall without the use of artificial roof or backfill material. Other methods, such as ascending multislice with backfill, may have application to thick, steeply dipping western seams. The easiest condition in which to initially use multislice mining may be a thick seam containing a substantial rock parting that can be used as a lower slice roof.

The use of artificial roof (wire mesh or other material) is considered currently too expensive to compete in demanding U.S. coal markets. Similarly, simultaneous multislice and the use of stowing or backfill material are also considered expensive. Simultaneous multislice productivity can be reduced by the requirement to keep a constant distance between faces, which may require one face to wait on the other during breakdowns. Improvements in multislice technology, such as mechanized artificial roof installation may, in the future, make some methods more cost competitive.

GROUND CONTROL AND SPONTANEOUS COMBUSTION

Ground control in lower slices is a major safety concern. If a roof fall occurs in lower slice development entries or longwall faces, it might propagate into the upper slice gob, allowing rubblized gob material to fall into lower slice workings. To prevent this occurrence, some method is needed to separate the upper and lower slices. Artificial roof material is frequently used for this purpose, but requires extra expense, and its installation may slow the longwall face, reducing productivity. Some western seams contain rock partings that now prevent recovery of the section of the seam above or below. The parting, if sufficiently competent, might be used to separate the slices and provide a lower slice roof. Another means to reduce the risk of a lower slice roof fall propagating into upper slice gob is to allow the upper slice gob to consolidate. If the rock split is to be used as lower slice roof, its competency should be thoroughly investigated prior to mining.

For purposes of planning and ground control analysis, multislice mining can be divided into four stages: (1) access, (2) development, (3) longwall mining, and (4) face recovery. Successful completion of each of these stages is necessary to successful multislice mining. During the access stage, development entries must be driven to the lower slice. If a rock-split lower slice roof is used, then the entries must penetrate through the split. Zones of high abutment stresses on the panel edges and ends should be avoided or roof support increased in these areas. Development entries should also avoid abutment stress zones and should be designed to provide maximum protection against roof fall. Longwall faces should be situated to obtain best possible ground control conditions. During recovery of the face, the integrity of the rock split used for lower slice roof should be ensured.

Ground control observations during multiple seam mining and measurements of gob pressure indicate that a zone of decreased vertical stress exists beneath upper slice gob. This destressed zone is generally a favorable location for lower slice workings. A corresponding high stress zone exists on panel edges, and it should be avoided. Commonly, multislice layouts have lower slice workings situated entirely beneath upper slice gob. The lower slice entries are inset horizontally from upper slice entries to avoid abutment stresses.

A joint industry-Bureau test of multislice mining is planned at a deep mine in western Colorado. The lower slice layout incorporates head-tail entries inset 60 ft inside upper slice entries and two-entry development. Standard three-entry development was not selected because it has four-way intersections that might decrease roof stability. Retreat longwall is planned to permit probing lower slice ground control conditions prior to committing longwall equipment.

Spontaneous combustion may be a serious problem if multislice mining is used in susceptible western thick seams. Leakage of spontaneous combustion gaseous products, such as carbon monoxide, from upper slice gob into lower slice workings would be a serious hazard to miners. Separating upper and lower slices becomes important from both ground control and spontaneous combustion perspectives. In the case of spontaneous combustion, a seal

between the slices becomes highly desirable. Measures that have been taken to provide the seal include allowing time for gob consolidation, injecting water to accelerate the consolidation, and injecting cementitious material, washery waste, or loess mud to solidify the lower part of the upper slice gob.

GEOLOGY

The geology of the coal seam, roof, and floor is important in multislice mining as in standard longwall. The geologic factors that are especially important in multislice mining are (1) coal thickness, (2) the competency of the rock split separating the slices, and (3) factors affecting gob consolidation. A decrease in seam thickness caused by geologic anomalies or thinning could reduce thickness below equipment minimum heights. The competency of the rock split separating the slices depends on its thickness, bedding planes, and lithology. These features are determined by the original depositional environment of the thick seam. Other features, such as joints and fractures, also affect the competency of the rock split. The time required for upper slice gob to consolidate and the consolidation reached depends on the gob material, its susceptibility to water, the amount of water present, and overburden pressure. Years may be required for some gobs to consolidate.

COST SENSITIVITY ANALYSIS

An analysis was done to determine the sensitivity of combined development and longwall operating costs to the type of lower slice development, layout dimensions, and other variables. Two cases were examined. The first case requires separate head-tail entries for each lower slice longwall and in the second case, adjacent lower slices share a single development system. In both cases, wider upper slice faces (and correspondingly wider lower slices) increased productivity and lowered cost. Case 2 had higher costs because the long tram distances required for the development continuous miner reduced development rates and required the longwall to remain idle until development caught up. The cost of accessing the lower slice through the intermediate rock split does not appear to greatly increase cost.

REMAINING PROBLEMS

Although multislice mining has not yet been used in the United States, its use appears technically and economically feasible in thick western coal seams. A number of questions need to be answered before the method gains broad acceptance by the mining industry. They include actual costs and productivities, best development system and placement of lower slice entries, and lower slice roof support. Scheduling of lower slice development may be a problem if that development cannot keep pace with longwall faces. Spontaneous combustion may be a safety problem in susceptible seams. Ventilation is an important consideration, but was not analyzed in this report. It is possible that the answers to these questions will be mine specific, and actual operating experience will be needed to get the answers.

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